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(54) Projection optical system and projection exposure apparatus using the same

(57) A projection optical system includes a plurality of positive lens groups having a positive refractive power, and at least one negative lens group having a negative refractive power, wherein, when L is a conjugate distance of the projection optical system and $\Sigma\phi_0$ is the sum of powers of the or each negative lens group, a relation $|L \times \Sigma\phi_0| > 17$ is satisfied, wherein, when h is a height of an axial marginal light ray and h_b is a height of a most abaxial chief ray, at least two aspherical surfaces

are formed on surfaces which satisfy a relation $|h_b/h| > 0.35$, wherein, when $\Delta ASPH$ is an aspherical amount of each aspherical surface, a relation $|\Delta ASPH/L| > 1.0 \times 10^{-6}$ is satisfied, and wherein the at least two aspherical surfaces include regions in which, from a central portion toward a peripheral portion of the surface, their local curvature powers change with mutually opposite signs.

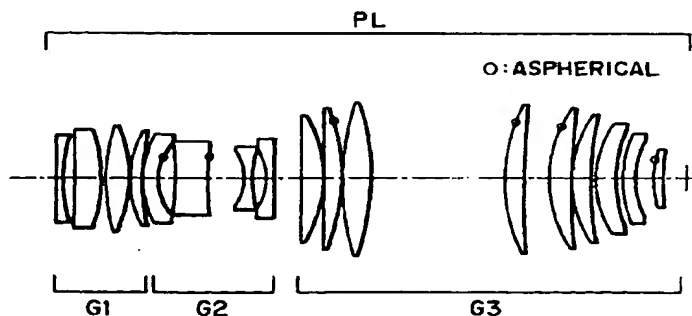


FIG. 1

Description

FIELD OF THE INVENTION AND RELATED ART

[0001] This invention relates to a projection optical system and a projection exposure apparatus using the same. More particularly, the invention is suitably applicable to a projection exposure process for printing a reticle pattern on a photosensitive substrate in accordance with a step-and-repeat method or a step-and-scan method, for manufacture of large-integration microdevices or semiconductor devices of submicron or quarter-micron order, such as IC, LSI, CCD, or liquid crystal panel, for example.

[0002] Generally, in a projection exposure apparatus, a reticle having an electronic circuit pattern formed thereon is illuminated with light (exposure light) from an illumination system (illumination optical system) and the pattern is projected onto a wafer through a projection optical system.

[0003] With an increasing density of a semiconductor device, strict requirements have been applied to the performance or specification of a projection optical system. Generally, for a higher resolution, attempts have been made in relation to shortening the wavelength of exposure light, better correction of aberrations of a projection optical system, or enlargement of the numerical aperture (NA) of a projection optical system.

[0004] As regards the exposure light, light of i-line lamp or laser light of an excimer laser such as KrF or ArF, for example, is used. Further, use of light from F₂ excimer laser has been proposed.

[0005] As regards enlargement of the numerical aperture (NA) of a projection optical system, the NA is being increased from 0.6 to 0.65, and then to 0.7.

[0006] As regards aberration correction, many attempts have been made so that a dual-telecentric system (being telecentric on object and image sides) is defined to reduce image distortion resulting from a warp of a reticle or a wafer and, on the other hand, distortion attributable to the projection optical system is reduced as much as possible. Also, the image plane width (field curvature amount) of best image points at each image heights is minimized, while the contrast gain at each image heights are uniformed as much as possible.

[0007] On the other hand, semiconductor device manufacturing processes use many reticle patterns or linewidths and, in accordance with them, the illumination condition is changed variously to obtain a best pattern image. In order to minimize differences in distortion or image plane flatness, for example, under different illumination conditions, coma aberrations at each image heights are reduced to attain registration of the image plane.

[0008] Further, while the throughput of a projection exposure apparatus is an important factor, the chip size has been enlarged to increase the throughput. The exposure region of the projection optical system is enlarged to meet this.

[0009] As regards a projection optical system for use in a projection exposure apparatus, Japanese Laid-Open Patent Applications, Laid-Open No. 105861/1997, No. 48517/1998, and No. 79345/1998 have proposed a projection optical system wherein all lens systems are defined by spherical surfaces.

[0010] Japanese Published Patent Application, Publication No.48089/1995 and Japanese Laid-Open Patent Applications, Laid-Open No. 128592/1995, No. 179204/1996, No. 34593/1993, No. 197791/1998, No. 154657/1998, No. 325922/1998, No. 333030/1998, and No. 6957/1999, have proposed a projection optical system wherein an aspherical surface is used for aberration correction.

[0011] In projection optical systems, in order that the shortening of the exposure wavelength and enlargement of the numerical aperture as well as a relatively large exposure region are satisfied while a good optical performance with less change in performance over various illumination modes is held, it is necessary to appropriately set the refractive powers of lens groups (lens units) as well as the lens structures of them.

[0012] Generally, in order to obtain a good optical performance with less performance change, the refractive power of each lens group (unit) should be made smaller to reduce the aberration amount to be produced in each lens group or, alternatively, the number of lenses to be used in each lens group should be enlarged to expand the degree of freedom in regard to aberration correction.

[0013] Therefore, if use of a shortened exposure wavelength and an enlarged numerical aperture (NA) as well as a wide exposure area are all desired, it necessarily results in enlargement of the lens conjugate distance (object-to-image distance) or an increase in the lens diameter or in the number of lenses, which causes inconveniences such as bulkiness in weight or thickness of the whole lens system.

[0014] Then, in that occasion, there arises a problem of deterioration of the imaging performance due to lens deformation attributable to an environmental change or a lens assembling precision. With enlargement of the lens diameter, deformation of a lens due to the weight thereof becomes large. Additionally, if a desired performance is to be accomplished within a certain conjugate distance, a larger number of lenses have to be used. Therefore, the thickness of each lens has to be reduced, and the lens deformation due to the weight thereof grows more. With a large lens deformation, the curvature radius of each surface of a lens is deviated from a design value, which causes degradation of the imaging performance. Further, while lenses are held by a metal holding element, in a strict sense and due to a machining precision, it is difficult for such metal holding element to hold the lenses uniformly. Therefore, if the lens deformation due to

the weight thereof becomes large and the lens deforms asymmetrically with respect to an optical axis, an asymmetric aberration is produced thereby. This is a large factor for deterioration of the imaging performance.

[0015] Further, with regard to the design performance, there are problems in relation to changes in the best imaging position depending on the linewidth (pattern linewidth), changes in the image point position or contrast depending on the image height, changes in distortion between different illumination conditions, and changes in image plane flatness, for example.

[0016] A change in the best imaging position depending on the linewidth is attributable mainly to a remaining spherical aberration not corrected. A change in image point position or contrast depending on the image height is attributable to a change in sagittal and meridional image planes at each image height, or to a change in astigmatism and comma.

A change in distortion or in image plane flatness between different illumination conditions results from a remaining distortion amount or an aberration amount in a region upon a pupil plane, passed by light rays, under different illumination conditions. The change in aberration such as described above becomes much notable if the shortening of exposure wavelength, the enlargement of numerical aperture and a wide exposure area are pursued more.

[0017] There is another problem that, in the short wavelength region of a light source such as an excimer laser, a usable lens material is limited to silica (quartz) and fluorite. This is mainly because of a decreased transmission factor. In an optical system having many lenses and a large total glass thickness, the exposure amount upon a wafer becomes very small such that the throughput is lowered very much. Further, there may occur a shift of the focal point position or a change in aberration.

[0018] In order to meet enlargement of integration of a semiconductor chip, further shortening of the wavelength of exposure light as well as further enlargement of the numerical aperture of a projection optical system are desired. However, it is very difficult to accomplish a required optical performance while suppressing enlargement in weight and thickness of the whole lens system and production of lens deformation due to the weight thereof. Currently, design optimization is made such that the refractive power of each lens group is made smaller and the number of lenses to be used is made larger.

[0019] In the projection optical systems disclosed in Japanese Laid-Open Patent Applications, Laid-Open No. 105861/1997, No. 48517/1998, and No. 79345/1998, all lenses are formed with spherical surfaces. The number of lenses is 27 to 30. The numerical aperture (NA) is about 0.6.

[0020] With such structure, however, if the NA is made larger, aberration correction becomes very difficult to accomplish as long as the same lens number is held. Alternatively, the total lens length has to be enlarged, and also the lens diameter has to be made larger. Even if the lens number is made very large for correction of aberration, since there is substantially no space for addition of lenses, the thickness of each lens must be made small or, alternatively, the total lens length has to be made quite large.

[0021] Any way, the lens deformation due to the weight thereof becomes notable, and the whole lens system becomes bulky. Moreover, if a light source of a short wavelength region is used, the transmission factor decreases due to large absorption by the lens material. In an optical system having lenses of a large number such as disclosed in these documents, the exposure amount upon a wafer decreases much more and the throughput is lowered considerably. Further, the shift of the focal point position or the change in aberration becomes large.

[0022] The projection optical systems disclosed in Japanese Published Patent Application, Publication No. 48089/1995 and Japanese Laid-Open Patent Application, Laid-Open No. 128592/1995, have a small numerical aperture (NA). Also, the exposure area is narrow. Because the power of a negative lens group used is small, the optical system is disadvantageous in respect to correction of the Petzval sum. If enlargement of the NA or expansion of the exposure region is attempted in this optical system, particularly the field curvature would be much worse. Further, since, in both cases, the projection optical system is not made telecentric on the object side, any curvature of a reticle would directly produce image distortion.

[0023] In the projection optical system disclosed in Japanese Laid-Open Patent Application, Laid-Open No. 179204/1996, an aspherical surface is formed on the surface closest to the wafer side. However, no particular discussion is made in relation to the aspherical surface. As for the imaging performance, correction of distortion, field curvature and astigmatism is insufficient. There remain large aberrations such as distortion of 26.7 nm and 11.7 nm as well as abaxial astigmatism of 1.262 micron and 0.896 micron.

[0024] The projection optical system disclosed in Japanese Laid-Open Patent Application, Laid-Open No. 34593/1993 uses an aspherical surface, and the lens system is provided by a smaller number of lenses to keep the lens transmission factor and for correction of aberrations. However, as regards the numerical aperture (NA) which largely contributes to the resolution, it is very small as 0.45. Also, the lens system has a very small exposure area of 10x10 to 15x15. According to the disclosure, aspherical surfaces are introduced into a negative second group and a positive fourth group, mainly for correction of spherical aberration. The power of the negative second group is enlarged while, on the other hand, an aspherical surface is added to the second group for correction of spherical aberration based on the balance with other positive lens groups. Also, an aspherical surface is introduced into a fourth group having a large axial light flux diameter, for correction of spherical aberration.

[0025] However, in this projection optical system, the height of axial marginal light ray of the second group is very low as compared with those of the third and fourth groups and, therefore, correcting the spherical aberration with the introduction of an aspherical surface is practically very difficult. The reason is that the third-order spherical aberration coefficient is proportional to the fourth power of the height "h" of axial marginal light ray.

[0026] Also, the height of outermost abaxial chief ray of the second group is very low, and the light goes just along the optical axis. Therefore, although the aspherical surface itself may function to correct aberrations such as distortion, field curvature or astigmatism while keeping the telecentricity on the object side, the effect is small. The reason is that the third-order astigmatism coefficient or field curvature coefficient is proportional to the second power of the chief ray height, and the distortion coefficient is proportional to the third power of the chief ray height.

[0027] According to this example, even if it is attempted to meet a larger numerical aperture (about 0.65) or enlargement of the exposure region (\varnothing is about 27.3 mm), since the power of the second group which bears most of the negative power is made very small, the Petzval sum can not be corrected. As a result, field curvature and astigmatism become worse. Additionally, as the light flux on the object side becomes large with enlargement of the numerical aperture, since the positive first group and negative second group on the object side (which function mainly to correct the field curvature, distortion and telecentricity on the object side) are provided by only a single lens, respectively, the load for aberration correction to be borne by these lens groups becomes considerably heavy. Thus, it becomes very difficult to keep good imaging performance.

[0028] The projection optical system disclosed in Japanese Laid-Open Patent Application, Laid-Open No. 197791/1998, provides a relatively wide exposure area and a relatively high resolution with use of a smaller number of lenses. While the exposure area is about $\varnothing 25 - \varnothing 29$, the numerical aperture is 0.48 - 0.50. However, this is still insufficient.

[0029] The projection optical system disclosed in Japanese Laid-Open Patent Application, Laid-Open No. 154657/1998, uses an aspherical surface. However, as stated, this aspherical surface is not designed to correct aberrations to provide a projection optical system of particular specifications. Rather, it is designed to correct higher order aberrations resulting from an error in production or adjustment of the components of the projection optical system.

[0030] Since the optical design is made entirely on a spherical system, even if the manufacturing error can be corrected by the aspherical surface, a performance higher than the design performance of the spherical system is not be attainable thereby. In fact, the aspherical amount is very small. Therefore, it is very difficult to solve the above-described problem, in an attempt to meet a larger numerical aperture.

[0031] The projection optical system disclosed in Japanese Laid-Open Patent Application, Laid-Open No. 325922/1998, comprises five lens groups, wherein one of first and second lens groups is provided with one aspherical surface, and one of fourth and fifth lens groups is provided with one aspherical surface. It is intended that, with a smaller number of lenses, mainly distortion and spherical aberration are corrected.

[0032] In the embodiments disclosed therein, the numerical aperture is 0.6. Moreover, no aspherical surface is used for the fourth lens group. While field curvature and astigmatism may be corrected well, there remain higher order components of "under" spherical aberration. Also, the distortion aberration is large as about 30 nm at the largest image height.

[0033] In this document, it is proposed to use an aspherical surface for a surface by which a large aberration correction effect is attainable. However, further details are not discussed any more. Therefore, aberrations may become worse if it is attempted to meet the numerical aperture enlargement.

[0034] If use of additional lenses is attempted to expand the degree of freedom for correction, although there is a small space at the image plane side and the spherical aberration may be corrected, in the region of the first to third groups at the object side, there are lenses disposed tightly. Thus, no lens can be added there. It is difficult to correct field curvature, astigmatism and distortion, for example. If the lens thickness is made small and an additional lens is inserted, then, the lens deformation will occur due to the weight of the lens.

[0035] The projection optical system disclosed in Japanese Laid-Open Patent Application, Laid-Open No. 333030/1998 uses aspherical surfaces and, according to the disclosure, it accomplishes NA of 0.63 - 0.75 and an exposure area of $\varnothing 27 - 30$ mm, with a smaller number of lenses of about fifteen (15). According to the disclosure, the lens system comprises positive two groups, wherein a first group at a wafer side is a microscope objective lens and a second group at a reticle side is a Gaussian type lens, by which sagittal comas produced in these lens groups are cancelled with each other. At least one aspherical surface is introduced into the wafer side first group, and also an aspherical surface is introduced to a large-diameter surface of the second group, for correction of spherical aberration.

[0036] However, the sagittal coma is not illustrated, and details of correction are unclear. According to simulations made by the inventors of the subject application, changes in sagittal halo due to the image height or meridional coma aberration (transverse aberration) are large.

[0037] Further, while spherical aberration and astigmatism may be corrected, as regards the distortion aberration, there remain large higher order components. The largest values in the first to fourth embodiments disclosed are 12 nm, 45 nm, 26 nm and 46 nm. As regards the telecentricity on the wafer side, in the first to fourth embodiments, changes in

image height per a focal depth of 1 micron are 24 nm, 22 nm, 19 nm and 19 nm.

[0038] Furthermore, since the distance from the wafer to the lens is very short as 11 - 12 mm, there is a large possibility of mechanical interference with a mechanism such as an autofocus unit.

[0039] The projection exposure apparatus disclosed in Japanese Laid-Open Patent Application, Laid-Open No. 6957/1999 provides a large NA (NA = 0.75 to 0.80) by use of aspherical surfaces. According to the disclosure, at least one aspherical surface is formed in the fourth or fifth lens group, for correction of aberrations very influential to enlargement of the NA, that is, sagittal coma aberration and higher order spherical aberration.

[0040] In the embodiments disclosed therein, however, sagittal coma is not illustrated. The number of lenses is large as 27 to 29. The optical conjugate distance is very long as 1200 - 1500 mm.

[0041] Therefore, if the light source has a wavelength in short wavelength region as an ArF excimer laser, for example, the exposure amount upon a wafer would be considerably lowered due to large absorption by the lens material, and the throughput becomes very low. Further, the thermal absorption of the lens causes shift of the focal point position or a change in aberration. Moreover, because of the large NA and long lens conjugate distance, the lens diameter is large as $\phi 284 - 400$ mm. Lens deformation due to the weight will be large. There is no space available, and thus suppressing the deformation by reducing the lens conjugate distance or increasing the number of lenses is difficult to do.

[0042] The lens number may be reduced by increasing the number of aspherical surfaces. However, in the first to fifth embodiments disclosed, while the number of aspherical surfaces used is increasing, all the lens system uses lenses of twenty-nine (29). Even in the fifth embodiment wherein a largest number of aspherical surfaces of six are used, there remains a sagittal image plane at the outermost abaxial image height of -0.484 micron. Further, distortion aberration is 13.1 nm, and also there remains higher order spherical aberration.

[0043] In the sixth and seventh embodiments disclosed, the distortion aberration is 33 nm and 58 nm, respectively. In the eighth and ninth embodiments, while the performance can not be confirmed due to insufficient data disclosure, the lens conjugate distance is extraordinarily large as 1500 mm.

25 SUMMARY OF THE INVENTION

[0044] It is an object of the present invention to provide a projection optical system and/or a projection exposure apparatus using the same, by which a larger numerical aperture and a wider exposure area can be well accomplished.

[0045] In accordance with a first aspect of the present invention, there is provided a projection optical system, comprising: a plurality of positive lens groups (units) having a positive refractive power; and at least one negative lens group (unit) having a negative refractive power; wherein, when L is a conjugate distance of said projection optical system and ϕ_0 is the sum of powers of the or each negative lens group, a relation

$$|L \times \phi_0| > 17 \quad (\phi_0 = \sum \phi_{0i} \text{ where } \phi_{0i} \text{ is the power of the } i\text{-th negative group}) \quad (1)$$

is satisfied; wherein, when h is a height of an axial marginal light ray and h_b is a height of a most abaxial chief ray, at least two aspherical surfaces are formed on surfaces which satisfy a relation

$$|h_b/h| > 0.35 \quad (2)$$

wherein, when ΔASPH is an aspherical amount of each aspherical surface, a relation

$$|\Delta\text{ASPH}/L| > 1.0 \times 10^{-6} \quad (3)$$

is satisfied; and wherein said at least two aspherical surfaces include regions in which, from a central portion toward a peripheral portion of the surface, their local curvature powers change with mutually opposite signs.

[0046] In a second aspect based on the first aspect, said at least two aspherical surfaces are formed on those surfaces up to one, in an order from the object side, which satisfies a relation

$$|h_b/h| > 0.35 \quad (2)$$

[0047] In a third aspect based on the first or second aspect, at least one of said at least two aspherical surfaces is provided in a negative lens group and includes a region in which, from the central portion to the peripheral portion of the surface, the local curvature power thereof gradually increases in the negative direction or gradually decreases in the positive direction.

[0048] In a fourth aspect based on the first to third aspects, the following relations

$$|L \times \phi_0| < 70 \quad (1a)$$

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$$lh_b/hl < 15 \quad (2a)$$

$$|\Delta ASPH/LI| < 0.02 \quad (3a)$$

are satisfied.

[0049] In accordance with a fifth aspect of the present invention, there is provided a projection optical system, comprising: a plurality of positive lens groups having a positive refractive power; and at least one negative lens group having a negative refractive power; wherein, when L is a conjugate distance of said projection optical system and \emptyset_0 is the sum of powers of the or each negative lens group, a relation

$$|L \times \emptyset_0| > 17 \quad (1)$$

is satisfied; wherein, when h is a height of an axial marginal light ray and h_b is a height of a most abaxial chief ray, at least one aspherical surface is formed on a surface in the negative lens group which satisfies a relation

$$lh_b/hl > 0.35 \quad (2)$$

wherein, when $\Delta ASPH$ is an aspherical amount of the aspherical surface, a relation

$$|\Delta ASPH/LI| > 1.0 \times 10^{-6} \quad (3)$$

is satisfied; and wherein said at least one aspherical surface includes a region in which, from a central portion toward a peripheral portion of the surface, a local curvature power thereof increases in the negative direction or decreases in the positive direction.

[0050] In a sixth aspect based on the fifth aspect, at least one aspherical surface is provided in a positive lens group and is formed upon one of the surfaces up to one, in an order from the object side, which satisfies a relation

$$lh_b/hl > 0.35 \quad (2)$$

and wherein said at least one aspherical surface includes a region in which, from the central portion to the peripheral portion of the surface, the local curvature power thereof gradually increases in the positive direction or gradually decreases in the negative direction.

[0051] In a seventh aspect based on the fifth or sixth aspect, the following relations

$$|L \times \emptyset_0| < 70 \quad (1a)$$

$$lh_b/hl < 15 \quad (2a)$$

$$|\Delta ASPH/LI| < 0.02 \quad (3a)$$

are satisfied.

[0052] In accordance with an eighth aspect of the present invention, there is provided a projection optical system, comprising: three lens groups of a lens group having a positive refractive power, a lens group having a negative refractive power, and a lens group having a positive refractive power, which are disposed in this order from the object side; wherein, when L is a conjugate distance of said projection optical system and \emptyset_0 is the power of said second negative refractive power lens group, a relation

$$|L \times \emptyset_0| > 17 \quad (1)$$

is satisfied; wherein, when h is a height of an axial marginal light ray and h_b is a height of a most abaxial chief ray, at least two aspherical surfaces are formed on surfaces which satisfy a relation

$$lh_b/hl > 0.35 \quad (2)$$

wherein, when $\Delta ASPH$ is an aspherical amount of each aspherical surface, a relation

$$|\Delta ASPH/LI| > 1.0 \times 10^{-6} \quad (3)$$

is satisfied.

[0053] In a ninth aspect based on the eighth aspect, said at least two aspherical surfaces include regions in which, from a central portion toward a peripheral portion of the surface, their local curvature powers change with mutually opposite signs.

[0054] In a tenth aspect based on the eighth or ninth aspect, an aspherical surface is provided in the positive lens group closest to the object side, which aspherical surface includes a region in which, from the central portion to the peripheral portion of the surface, the local curvature power thereof gradually increases in the positive direction or gradually decreases in the negative direction.

[0055] In an eleventh aspect based on the eighth to tenth aspects, an aspherical surface is provided in the positive lens group closest to the image plane side, which aspherical surface includes a region in which, from the central portion to the peripheral portion of the surface, the local curvature power thereof gradually increases in the negative direction or gradually decreases in the positive direction.

[0056] In a twelfth aspect based on the eighth to eleventh aspects, a or each lens group disposed after, in an order from the object side to the image plane side, the sign of an abaxial chief ray height is reversed, has at least one aspherical surface formed thereon.

[0057] In a thirteenth aspect based on the eighth to twelfth aspects, in the positive lens group disposed closest to the image plane side, a second lens thereof in an order from the image plane side comprises a negative lens having a concave surface facing to the image side, and a lens of that lens group, which lens is closest to the image plane side, comprises a positive lens having a concave surface facing to the image plane side.

[0058] In a fourteenth aspect based on the eighth to thirteenth aspects, at least one aspherical lens with an aspherical surface has a plane surface formed on its side opposite to the aspherical surface thereof.

[0059] In a fifteenth aspect based on the eighth to thirteenth aspects, each aspherical lens with an aspherical surface has a plane surface formed on its side opposite to the aspherical surface thereof.

[0060] In a sixteenth aspect based on the eighth to thirteenth aspects, at least one aspherical lens provided in said projection optical system has two aspherical surfaces formed on the opposite sides thereof.

[0061] In a seventeenth aspect based on the eighth to thirteenth aspects, each aspherical lens provided in said projection optical system has two aspherical surfaces formed on the opposite sides thereof.

[0062] In an eighteenth aspect based on the eighth to seventeenth aspects, the following relations

$$|L \times \phi_0| < 70 \quad (1a)$$

$$|h_b/h| < 15 \quad (2a)$$

$$|\Delta \text{ASPH}/L| < 0.02 \quad (3a)$$

are satisfied.

[0063] In accordance with a nineteenth aspect of the present invention, there is provided a projection optical system, comprising: a first lens group L1 having a positive refractive power, a second lens group L2 having a negative refractive power, a third lens group L3 having a positive refractive power, a fourth lens group L4 having a negative refractive power, and a fifth lens group L5 having a positive refractive power, which are disposed in this order from the object side; wherein, when h is a height of an axial marginal light ray and h_b is a height of a most abaxial chief ray, at least two aspherical surfaces are formed on surfaces which satisfy a relation

$$|h_b/h| > 0.35 \quad (1)$$

wherein, when ASPH is a largest aspherical amount of each aspherical surface from an optical axis to a lens effective diameter and L is an object-to-image distance, each aspherical surface satisfies a relation

$$|\Delta \text{ASPH}/L| > 1.0 \times 10^{-6} \quad (2)$$

wherein said aspherical surfaces include regions in which, from a central portion to a peripheral portion of the surface, their local curvature powers change with mutually opposite signs.

[0064] In a twentieth aspect based on the nineteenth aspect, at least one of said at least two aspherical surfaces includes a region in which, from the central portion to the peripheral portion of the surface, the local curvature power thereof gradually increases in the negative direction.

[0065] In a twenty-first aspect based on the eighteenth or nineteenth aspect, at least one of said at least two aspherical surfaces is provided in a lens group having a negative refractive power.

[0066] In accordance with a twenty-second aspect of the present invention, there is provided a projection optical

system, comprising: a first lens group L1 having a positive refractive power, a second lens group L2 having a negative refractive power, a third lens group L3 having a positive refractive power, a fourth lens group L4 having a negative refractive power, and a fifth lens group L5 having a positive refractive power, which are disposed in this order from the object side; wherein, when h is a height of an axial marginal light ray and h_b is a height of a most abaxial chief ray, at least one aspherical surface is formed on a surface which satisfies a relation

$$|h_b/h| > 0.35 \quad (1)$$

wherein, when $\Delta ASPH$ is a largest aspherical amount of said aspherical surface from an optical axis to a lens effective diameter and L is an object-to-image distance, said aspherical surface satisfies a relation

$$|\Delta ASPH/L| > 1.0 \times 10^{-6} \quad (2)$$

wherein said aspherical surface includes a region in which, from a central portion to a peripheral portion of the surface, a local curvature power thereof gradually increases in the negative direction.

[0067] In a twenty-third aspect based on the nineteenth to twenty-second aspects, at least one aspherical lens provided in said projection optical system has a plane surface formed on its side opposite to the aspherical surface thereof.

[0068] In a twenty-fourth aspect based on the nineteenth to twenty-second aspects, each aspherical lens provided in said projection optical system has a plane surface formed on its side opposite to the aspherical surface thereof.

[0069] In a twenty-fifth aspect based on the nineteenth to twenty-second aspects, at least one aspherical lens provided in said projection optical system has aspherical surfaces formed on the opposite sides thereof.

[0070] In a twenty-sixth aspect based on the nineteenth to twenty-second aspects, each aspherical lens provided in said projection optical system has aspherical surfaces formed on the opposite sides thereof.

[0071] In a twenty-seventh aspect based on the nineteenth to twenty-second aspects, the following relations

$$|h_b/h| < 15 \quad (2a)$$

$$|\Delta ASPH/L| < 0.02 \quad (3a)$$

are satisfied.

[0072] In a twenty-eighth aspect based on the nineteenth to twenty-seventh aspects, when L is an object-to-image distance of said projection optical system and $\Sigma \phi_0$ is the sum of powers of the negative lens groups, a relation

$$|L \times \Sigma \phi_0| > 17 \quad (\Sigma \phi_0 = \Sigma \phi_{0i} \text{ where } \phi_{0i} \text{ is the power of the } i\text{-th negative group}) \quad (3)$$

is satisfied.

[0073] In a twenty-ninth aspect based on the twenty-eighth aspect, a relation

$$|L \times \Sigma \phi_0| < 70 \quad (1a)$$

is satisfied.

[0074] In accordance with a thirtieth aspect of the present invention, there is provided a projection optical system, comprising: a first lens group L1 having a positive refractive power, a second lens group L2 having a negative refractive power, a third lens group L3 having a positive refractive power, a fourth lens group L4 having a negative refractive power, a fifth lens group L5 having a positive refractive power, a sixth lens group having a negative refractive power, and a seventh lens group having a positive refractive power, which are disposed in this order from the object side; wherein one or more aspherical surfaces are formed in said projection optical system; and wherein, when $\Delta ASPH$ is a largest aspherical amount of each aspherical surface from an optical axis to a lens effective diameter and L is an object-to-image distance, at least one aspherical surface satisfies a relation

$$|\Delta ASPH/L| > 1.0 \times 10^{-6} \quad (3)$$

[0075] In a thirty-first aspect based on the thirtieth aspect, at least one aspherical surface is provided between a first lens surface closest to the object side and a stop position.

[0076] In a thirty-second aspect based on the thirtieth or thirty-first aspect, when h is a height of an axial marginal light ray and h_b is a height of a most abaxial chief ray, at least one aspherical surface is formed on a surface which satisfies a relation

$$|h_b/h| > 0.35 \quad (2)$$

[0077] In a thirty-third aspect based on the thirty-second aspect, at least two aspherical surfaces are formed in said projection optical system.

5 **[0078]** In a thirty-fourth aspect based on the thirtieth to thirty-third aspects, the aspherical surface is provided in a lens group having a negative refractive power, and at least one aspherical surface in the lens group of negative refractive power includes a region in which, from a central portion to a peripheral portion of the surface, a local curvature power thereof gradually increases in the negative direction.

10 **[0079]** In a thirty-fifth aspect based on the thirtieth to thirty-fourth aspects, at least two aspherical surfaces include regions in which, from a central portion to a peripheral portion of the surface, their local curvature powers change with mutually opposite signs.

[0080] In a thirty-sixth aspect based on the thirtieth to thirty-fifth aspects, at least one aspherical lens provided in said projection optical system has a plane surface formed on its side opposite to the aspherical surface thereof.

15 **[0081]** In a thirty-seventh aspect based on the thirtieth to thirty-fifth aspects, each aspherical lens provided in said projection optical system has a plane surface formed on its side opposite to the aspherical surface thereof.

[0082] In a thirty-eighth aspect based on the thirtieth to thirty-fifth aspects, at least one aspherical lens provided in said projection optical system has aspherical surfaces formed on the opposite sides thereof.

[0083] In a thirty-ninth aspect based on the thirtieth to thirty-fifth aspects, each aspherical lens provided in said projection optical system has aspherical surfaces formed on the opposite sides thereof.

20 **[0084]** In a fortieth aspect based on the thirtieth to thirty-ninth aspects, when L is an object-to-image distance of said projection optical system and \varnothing is the sum of powers of the negative lens groups, a relation

$$|L \times \varnothing_0| > 17 \quad (\varnothing_0 = \sum \varnothing_{0i} \text{ where } \varnothing_{0i} \text{ is the power of the } i\text{-th negative group}) \quad (1)$$

25 is satisfied.

[0085] In a forty-first aspect based on the thirtieth to fortieth aspects, a relation

$$|\Delta \text{ASPH}/L| < 0.02 \quad (3a)$$

30 is satisfied.

[0086] In a forty-second aspect based on the thirty-second to thirty-third aspects, a relation

$$h_b/h < 15 \quad (2a)$$

35 is satisfied.

[0087] In a forty-third aspect based on the fortieth aspect, a relation

$$|L \times \varnothing_0| < 70 \quad (1a)$$

40 is satisfied.

[0088] In accordance with a forty-fourth aspect of the present invention, there is provided a projection exposure apparatus for projecting a pattern of a first object, illuminated with light from a light source, onto a second object by use of a projection optical system as recited above.

45 **[0089]** In accordance with a forty-fifth aspect of the present invention, there is provided a projection exposure apparatus for projecting a pattern of a first object, illuminated with light from a light source, onto a second object by use of a projection optical system as recited above, while scanningly moving the first and second objects in a direction perpendicular to an optical axis of said projection optical system, in synchronism with each other and at a speed ratio corresponding to a projection magnification of said projection optical system.

50 **[0090]** In accordance with a forty-sixth aspect of the present invention, there is provided a device manufacturing method, comprising the steps of: exposing a wafer to a device pattern of a reticle by use of a projection exposure apparatus as recited above; and fabricating a device from the exposed wafer.

[0091] These and other objects, features and advantages of the present invention will become more apparent upon a consideration of the following description of the preferred embodiments of the present invention taken in conjunction with the accompanying drawings.

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BRIEF DESCRIPTION OF THE DRAWINGS

[0092]

- 5 Figure 1 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 1 of the present invention.
- Figure 2 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 1.
- Figure 3 illustrates aberrations of a projection optical system according to Numerical Example 1.
- 10 Figure 4 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 2 of the present invention.
- Figure 5 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 2.
- Figure 6 illustrates aberrations of a projection optical system according to Numerical Example 2.
- 15 Figure 7 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 3 of the present invention.
- Figure 8 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 3.
- Figure 9 illustrates aberrations of a projection optical system according to Numerical Example 3.
- 20 Figure 10 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 4 of the present invention.
- Figure 11 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 4.
- Figure 12 illustrates aberrations of a projection optical system according to Numerical Example 4.
- 25 Figure 13 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 5 of the present invention.
- Figure 14 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 5.
- Figure 15 illustrates aberrations of a projection optical system according to Numerical Example 5.
- 30 Figure 16 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 6 of the present invention.
- Figure 17 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 6.
- Figure 18 illustrates aberrations of a projection optical system according to Numerical Example 6.
- 35 Figure 19 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 7 of the present invention.
- Figure 20 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 7.
- Figure 21 illustrates aberrations of a projection optical system according to Numerical Example 7.
- 40 Figure 22 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 8 of the present invention.
- Figure 23 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 8.
- Figure 24 illustrates aberrations of a projection optical system according to Numerical Example 8.
- 45 Figure 25 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 9 of the present invention.
- Figure 26 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 9.
- Figure 27 illustrates aberrations of a projection optical system according to Numerical Example 9.
- 50 Figure 28 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 10 of the present invention.
- Figure 29 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 10.
- Figure 30 illustrates aberrations of a projection optical system according to Numerical Example 10.
- 55 Figure 31 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 11 of the present invention.
- Figure 32 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 11.

Figure 33 illustrates aberrations of a projection optical system according to Numerical Example 11.

Figure 34 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 12 of the present invention.

5 Figure 35 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 12.

Figure 36 illustrates aberrations of a projection optical system according to Numerical Example 12.

Figure 37 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 13 of the present invention.

10 Figure 38 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 13.

Figure 39 illustrates aberrations of a projection optical system according to Numerical Example 13.

Figure 40 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 14 of the present invention.

15 Figure 41 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 14.

Figure 42 illustrates aberrations of a projection optical system according to Numerical Example 14.

Figure 43 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 15 of the present invention.

20 Figure 44 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 15.

Figure 45 illustrates aberrations of a projection optical system according to Numerical Example 15.

Figure 46 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 16 of the present invention.

25 Figure 47 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 16.

Figure 48 illustrates aberrations of a projection optical system according to Numerical Example 16.

Figure 49 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 17 of the present invention.

30 Figure 50 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 17.

Figure 51 illustrates aberrations of a projection optical system according to Numerical Example 17.

Figure 52 is a schematic view for explaining an optical function of a three-group system into which the present invention is applied.

35 Figure 53 is a schematic view for explaining an optical function of a five-group system into which the present invention is applied.

Figure 54 is a schematic view for explaining an optical function of a seven-group system into which the present invention is applied.

Figure 55 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 18 of the present invention.

40 Figure 56 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 18.

Figure 57 illustrates aberrations of a projection optical system according to Numerical Example 18.

Figure 58 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 19 of the present invention.

45 Figure 59 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 19.

Figure 60 illustrates aberrations of a projection optical system according to Numerical Example 19.

Figure 61 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 20 of the present invention.

50 Figure 62 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 20.

Figure 63 illustrates aberrations of a projection optical system according to Numerical Example 20.

Figure 64 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 21 of the present invention.

55 Figure 65 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 21.

Figure 66 illustrates aberrations of a projection optical system according to Numerical Example 21.

Figure 67 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, accord-

ing to Numerical Example 22 of the present invention.

Figure 68 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 22.

Figure 69 illustrates aberrations of a projection optical system according to Numerical Example 22.

Figure 70 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 23 of the present invention.

Figure 71 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 23.

Figure 72 illustrates aberrations of a projection optical system according to Numerical Example 23.

Figure 73 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 24 of the present invention.

Figure 74 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 24.

Figure 75 illustrates aberrations of a projection optical system according to Numerical Example 24.

Figure 76 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 25 of the present invention.

Figure 77 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 25.

Figure 78 illustrates aberrations of a projection optical system according to Numerical Example 25.

Figure 79 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 26 of the present invention.

Figure 80 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 26.

Figure 81 illustrates aberrations of a projection optical system according to Numerical Example 26.

Figure 82 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 27 of the present invention.

Figure 83 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 27.

Figure 84 illustrates aberrations of a projection optical system according to Numerical Example 27.

Figure 85 is a lens sectional view of a projection optical system for use in a projection exposure apparatus, according to Numerical Example 28 of the present invention.

Figure 86 is a graph for explaining changes in a local curvature power of an aspherical surface of a projection optical system according to Numerical Example 28.

Figure 87 illustrates aberrations of a projection optical system according to Numerical Example 28.

Figure 88 is a schematic view of an aspherical surface processing system usable in the present invention.

Figure 89 is a block diagram of a main portion of a semiconductor device manufacturing system according to an embodiment of the present invention.

Figure 90 is a flow chart of semiconductor device manufacturing processes.

Figure 91 is a flow chart for explaining details of a wafer process in the procedure of the flow chart of Figure 90.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0093] Preferred embodiments of the present invention will now be described with reference to the accompanying drawings.

[0094] In these lens sectional views, a reference character PL denotes a projection optical system, and a reference character Gi denotes the i-th lens group (i-th group) of the projection optical system, in an order from the object side (conjugate side of longer distance).

[0095] Denoted at IP is an image plane which corresponds to a wafer surface, when the projection optical system is used in a projection exposure apparatus. In the lens groups Gi, those lens groups having an odd number assigned for "i" are lens groups having a positive refractive power, while those lens groups having an even number assigned for "i" are lens groups having a negative refractive power.

[0096] Also those lens surfaces with a small circle added thereto are aspherical surfaces.

[0097] In each of Numerical Examples 1 - 5 and 18 and 19 shown in the lens sectional views of Figures 1, 4, 7, 10 and 13 and Figures 55 and 56, respectively, the projection optical system comprises three lens groups or lens units (three-group type) which have positive, negative, and positive refractive powers, respectively, in an order from the object side.

[0098] In each of Numerical Examples 6 - 11 and 20 - 24 shown in the lens sectional view of Figures 16, 19, 22, 25, 28 and 31 and Figures 61, 64, 67, 70 and 73, respectively, the projection optical system comprises five lens groups or

lens units (five-group type) which have positive, negative, positive, negative, and positive refractive powers, respectively, in an order from the object side.

[0099] In each of Numerical Examples 12 - 17 and 25 - 28 shown in the lens sectional view of Figures 34, 37, 40, 43, 47 and 50 and Figures 76, 79, 82 and 85, respectively, the projection optical system comprises seven lens groups or lens units (seven-group type) which have positive, negative, positive, negative, positive, negative, and positive refractive powers, respectively, in an order from the object side.

[0100] In these numerical examples, while appropriate power sharing is made through the whole lens system, aspherical surfaces are introduced to appropriate lens faces, by which a good optical performance is accomplished.

[0101] Projection optical systems according to the present invention provide a large numerical aperture and a wide exposure area.

[0102] To this end, the optical system as a whole comprises a plurality of lens groups including a lens group having a positive refractive power and a lens group having a negative refractive power, wherein the power sharing (refractive power sharing) is set appropriately.

[0103] In one preferred form of the present invention, for appropriate setting of power sharing, the condition as defined by equation (1) is set in regard to the product of the conjugate distance L of the lens system and the sum Σ of powers of negative lens group or groups. Generally, if the conjugate distance (object-to-image distance) L becomes longer, the total power Σ of the negative lens groups becomes smaller. If on the other hand the conjugate distance becomes shorter, the total power Σ of the negative lens groups becomes larger.

[0104] In one preferred form of the present invention, the product of the conjugate distance and the total power is set to be not less than 17. The total power of the negative refractive power lens group is therefore made larger, mainly for satisfactory correction of the curvature of image field and the astigmatism. If the lower limit of the condition of equation (1) is exceeded, the Petzval sum increases in the positive direction, such that satisfactory correction of the curvature of image field or astigmatism becomes difficult to accomplish.

[0105] The condition of equation (2) defines an appropriate surface for introduction of an aspherical surface, based on satisfaction of the condition (1). In conventional reduction projection optical systems, it is very difficult to satisfactorily correct distortion, curvature of image field, and astigmatism as well as transverse aberrations of meridional and sagittal, while maintaining the telecentricity.

[0106] This is because of the following reason. The telecentricity, distortion, curvature of image field, and astigmatism are all aberration amounts related to a principal ray passing through the center of a light flux. Although these aberrations depend on the placement and shape of lenses on the object side where, in the lens system as a whole, the height of the principal ray is high, practically it is very difficult to maintain, on one hand, the telecentricity with respect to principal rays from every object points on the object and, on the other hand, to refract the same principal ray so as to correct the distortion, the curvature of image field and the astigmatism.

[0107] Further, since on a lens surface those rays below the meridional are refracted at a height still higher than the principal ray, it is difficult to balance the meridional transverse aberration and aberration concerning these principal rays. Simultaneously, in order to correct the curvature of image field which has a tendency that it is "under" with higher image height, usually a concave lens is used to refract the light strongly. Then, however, the peripheral portion (sagittal halo) of the sagittal transverse aberration at high image heights further changes "over". Thus, it is difficult to balance them satisfactorily.

[0108] Enlarging the numerical aperture and widening the exposure area under these situations directly lead to further enlargement of the object side light flux and image height, and it amplifies the difficulties in aberration correction.

[0109] In one preferred form of the present invention, in consideration of the above, the condition of equation (2) is satisfied and an aspherical surface is formed on such surface having a large influence to abaxial principal rays, thereby to concentratedly and effectively correct the above-described aberrations to be improved. This effectively reduces the load for correction of other aberrations, and accomplishes a good optical performance.

[0110] If the lower limit of the condition of equation (2) is exceeded, the influence to axial marginal light rays increases, rather than to the abaxial principal rays, and therefore, the effect of correcting the aberrations to be improved diminishes. Thus, it becomes difficult to attain an enlarged numerical aperture and a wider exposure area.

[0111] For better understanding of the present invention, an optical function of a projection optical system when an aspherical surface is introduced thereto will now be described. Figures 52, 53 and 54 are schematic views, respectively, of power arrangement in examples wherein the whole lens system comprises three lens groups, five lens groups and seven lens groups, respectively.

[0112] Denoted in these drawings at R is a reticle as an object, and denoted at W is a wafer as an image plane. Solid lines depict axial marginal light rays and the surface height thereof is denoted by h . Broken lines depict most abaxial chief rays and the surface height thereof is denoted by h_p . The optical system is bi-telecentric, both on the object side and the image side.

[0113] In the reduction projection systems shown in Figures 52, 53 and 54, the object side numerical aperture corresponds to the product of the projection magnification and the image side numerical aperture (the term "numerical

aperture" referred to in this specification means the image side numerical aperture). Therefore, the axial marginal light is small at the object side and it is large at the image side.

[0114] For this reason, the height h is small at the object side, and it is large at the image side. To the contrary, because of the projection magnification, the height h_b of the most abaxial chief ray is high at the object side, and it is low at the image side.

[0115] Generally, at a surface where third order aberrations are large, there exist large higher-order aberrations. Thus, it is necessary for better aberration correction that an absolute value of the third order aberration coefficient at each surface is made small and that the value as a whole is made small. The distortion aberration coefficient is influential with the third power of h_b and the first power of h , and the curvature of field and astigmatism coefficients are influential with the second power of h_b and second power of h . The comma aberration coefficient is influential with the first power of h_{b1} and third power of h , and the spherical aberration coefficient is influential with the fourth power of h .

[0116] In Figure 52, the heights h and h_b that satisfy condition (2) are from the object surface to the lens groups G1 and G2. Thus, introducing at least one aspherical surface into the group G1 or G2 is a condition for better optical performance. When an aspherical surface is introduced into the lens group G1, the height h_b becomes highest and, therefore, it is very effective to control the distortion aberration coefficient.

[0117] Introducing an aspherical surface into the lens group G2 having a negative refractive power is effective to control mainly the field curvature and astigmatism aberration coefficients. Since however it is in a cancelling relation with the lens group G1 having a positive refractive power, the distortion aberration coefficient can also be controlled effectively.

[0118] Generally, at a surface having a large height h , using an aspherical surface contributes the spherical aberration coefficient or the comma aberration coefficient. Therefore, introducing an aspherical surface to the lens group G3 having a positive refractive power is effective for correction of spherical aberration or comma aberration.

[0119] Also in Figure 53, while condition (2) is satisfied between the object surface to the lens groups G1 and G2, since there are two lens groups of negative refractive power, it is advantageous in respect to correction of the Petzval sum (because the necessity of refracting light rays at a low positions so as to enlarge the power of the negative lens group is diminished). Further, the spacing between the lens groups G1 and G2 is made small. Therefore, the value of condition (2) in the group G2 is large as compared with the three-group type of Figure 52.

[0120] Thus, while introducing at least one aspherical surface into lens group G1 or G2 is a condition for better optical performance, the aberration correcting ability is larger than that of the three-group type lens system of Figure 52. The controllability of aberration coefficients in the lens groups G1 and G2 is similar to that of the three-group type lens system of Figure 52.

[0121] Here, because there are two negative lens groups included, correction of field curvature or astigmatism is easier than with the three-group type lens system of Figure 52. The load for aberration correction applied to the lens group G2 is smaller. As an alternative, aspherical surfaces may be introduced into lens groups G3, G4 and G5 of large height h , for correction of spherical aberration or comma aberration.

[0122] In Figure 54, condition (2) can be satisfied between the object surface and the lens groups G1, G2, G3 and G4. As compared with the three-group type lens system of Figure 52 and the five-group type lens system of Figure 53, the most abaxial chief ray can easily keep a high position relative to the axial marginal light ray. This is because there are three negative lens groups included which is advantageous to correction of Petzval sum, and because the spacings among the lens groups G1, G2, G3 and G4 are made small.

[0123] Thus, an aspherical surface can be introduced more effectively, and better optical performance can be accomplished.

[0124] Particularly, by introducing an aspherical surface to the lens group G1 or G2 showing a large value with respect to condition (2), distortion aberration, curvature of field and astigmatism can be corrected successfully. As regards lens groups G3 and G4, they are suitable mainly for correction of comma aberration and sagittal transverse aberration.

[0125] Using an aspherical surface in the lens group G5, G6 or G7 having large h is effective to correct spherical aberration or comma aberration.

[0126] While the optical function in relation to introduction of an aspherical surface has been described above, for more effective introduction of an aspherical surface in obtaining better imaging performance, the condition of equation (3) should preferably be satisfied.

[0127] Equation (3) defines a condition for the aspherical amount. If the lower limit of condition (3) is exceeded, the effect of aspherical surface does not function well even though the aspherical surface is used in design to obtain a good imaging performance.

[0128] For example, if the conjugate distance is 1000 mm and the wavelength used is 193 nm, from equation (2), ΔSPH is equal to 0.001 mm which corresponds to about ten Newton's rings. This is a sufficiently large value as an aspherical surface to be used in a projection optical system. Further, for more effective use of an aspherical surface, the following relation may be satisfied

$$|\Delta \text{ASPH}/L| > 1 \times 10^{-5}$$

to enlarge the aspherical amount.

[0129] The present invention enables effective introduction of an aspherical surface. However, there is a limit to apply a desired change in refractive power for aberration correction, by using a single aspherical surface to plural light beams from an object. Thus, preferably, at least two aspherical surfaces satisfying the above-described condition may be used, to share the aberration correcting function. A better result is attainable with this.

[0130] Further, conditions as defined by equations (1a), (2a) and (3a) mentioned above may preferably be satisfied, for much better correction of aberrations.

[0131] If the upper limit of the condition of equation (1a) is exceeded, the power of a negative lens group or groups having a negative refractive power becomes too strong. Therefore, the Petzval sum is over-corrected, and it becomes difficult to mainly correct the curvature of image field and astigmatism, satisfactorily.

[0132] Further, the lens diameter of a positive lens group having a positive refractive power becomes larger, or the number of lenses increases.

[0133] If the upper limit of the condition of equation (2a) is exceeded, lenses become too close to the object plane and the working distance can not be kept. If the magnification of the projection optical system is extraordinarily small, the working distance may be kept even though the condition is exceeded. However, an optical system having such a extraordinarily small magnification is not practical for use in lithography.

[0134] When the upper limit of the condition of equation (3a) is exceeded, the aspherical amount becomes too large, causing a large increase in the time necessary for lens machining. Further, higher order aberrations produced at the aspherical surface become strong, which makes the satisfactory correction of aberration very difficult.

[0135] Further, in relation to the change in curvature of an aspherical surface, the effect of using an aspherical surface can be enhanced significantly when at least one of the following conditions is satisfied.

(a1) There should be at least two aspherical surfaces having regions in which, from a central portion to a peripheral portion of the surface, their local curvature powers change with mutually opposite signs.

(a2) At least one aspherical surface provided in a negative lens group should include a region in which, from a central portion to a peripheral portion of the surface, the local curvature power thereof gradually increases in the negative direction, or gradually decreases in the positive direction.

(a3) At least one aspherical surface among the aspherical surfaces of (a1) and (a2) and provided in a positive lens group, should include a region in which, from a central portion to a peripheral portion of the surface, the local curvature power thereof gradually increases in the positive direction, or gradually decreases in the negative direction.

[0136] As regards correction of aberration by use of an aspherical surface, generally, an aspherical surface is introduced to a certain lens surface so as to reduce production of aberration at that surface (i.e., auxiliary introduction). An example is that, in a case of a convex single lens, since the spherical aberration is "under", an aspherical surface whose curvature becomes smaller in the peripheral portion is used to correct the spherical aberration.

[0137] In the present invention, as compared therewith, while reducing the number of lenses is aimed at on one hand, aspherical surfaces are introduced so as to cancel aberration in combination with other surfaces, to thereby accomplish good performance as well (i.e., positive introduction). By doing so, aberrations are corrected successfully.

[0138] More specifically, by satisfying the condition (a1), a relation of cancelling two aspherical surface powers is defined. By this, it is assured that a change in refractive power applied to an arbitrary light from an object produces a refractive power change with which plural aberrations can be minimized simultaneously, which are not attainable with use of only spherical surfaces or a lens having only one aspherical surface.

[0139] Higher order aberrations which can not be easily corrected, such as distortion, curvature of field, astigmatism, sagittal transverse aberration or meridional transverse aberration, in higher order regions, for example, can be well corrected by the function of the condition (a1) above.

[0140] Particularly, two aspherical surfaces are so distributed that one aspherical surface is provided in the first lens group G1 while another aspherical surface is provided in the second lens group G2, the telecentricity, distortion aberration, field of curvature can be corrected very well.

[0141] When both of the two aspherical surfaces are introduced into the second lens group G2, curvature of field, meridional and sagittal transverse aberrations, and distortion aberration can be corrected very well.

[0142] When two aspherical surfaces are introduced into the third lens group G3 and fourth lens group G4 of a seven-group type lens system of Figure 54, sagittal transverse aberration and coma aberration can be corrected very well.

[0143] Further, satisfying the condition (a2) is particularly effective for correction of curvature of field and meridional and sagittal transverse aberrations.

[0144] This is because, if the Petzval sum is well corrected, it is still difficult to correct sagittal field curvature having

a tendency of "under" and, therefore, as described, it is difficult to balance it with the meridional or sagittal transverse aberrations. In the present invention, by satisfying the condition (a2), particularly the power in the negative refractive power direction is made large to thereby correct the "under" portion of the field curvature toward the "over" side. This provides an additional advantage that the degree of freedom for correction of aberrations at surfaces other than the aspherical surface can be expanded significantly, such that meridional or sagittal transverse aberrations and distortion aberrations, for example, can be corrected very well.

[0145] As an important feature, satisfying the condition (a3) is particularly effective for correction of the object-side telecentricity and higher order distortion aberrations.

[0146] More specifically, in the present invention, the condition of equation (1) for making the power of a negative lens group large, enables correction of astigmatism or curvature of image field which relates to the Petzval sum. However, it influences the balance of telecentricity on the object side because of higher order negative powers, and higher order "under" distortion aberration is produced. When the condition (a3) is satisfied, the object-side telecentricity is well accomplished again. Simultaneously, an "over" distortion aberration in an opposite direction is produced to cancel it. Thus, the correction can be done well.

[0147] In addition, if plural aspherical surfaces are introduced, aberration correction can be done more successfully over the whole system. The spherical aberration and coma aberration can be corrected satisfactorily when aspherical surfaces are introduced into a lens group having a large axial marginal light ray height, that is, the third lens group G3 of Figure 52, the third, fourth and fifth lens groups G3, G4 and G5 of Figure 53, the fifth, sixth, and seventh lens groups G5, G6 and G7 of Figure 54, wherein each aspherical surface includes a region in which, from a central portion to a peripheral portion of the surface, the local curvature power thereof gradually increases in the negative direction (or decreases in the positive direction).

[0148] As described, in accordance with the present invention, the power sharing is set appropriately and an aspherical surface is provided at a suitable position. Also, an appropriate aspherical amount is set thereto, and the aspherical surface shape is determined to satisfy a predetermined condition or conditions. With this arrangement, distortion aberration, curvature of field, astigmatism, coma aberration and spherical aberration, for example, are well corrected while maintaining the dual-telecentricity. Thus, a projection optical system having a better optical performance is accomplished.

[0149] In a three-group type lens system, the effect of using an aspherical surface can be enhanced significantly when at least one of the following conditions is satisfied.

(b1) There should be at least two aspherical surfaces having regions in which, from a central portion to a peripheral portion of the surface, their local curvature powers change with mutually opposite signs.

(b2) At least one of aspherical surfaces provided in a positive lens group G1 which is closest to the object side, should include a region in which, from a central portion to a peripheral portion of the surface, the local curvature power thereof gradually increases in the positive direction, or gradually decreases in the negative direction.

(b3) At least one of aspherical surfaces provided in a positive lens group G3 which is closest to the image plane side, should include a region in which, from a central portion to a peripheral portion of the surface, the local curvature power thereof gradually increases in the negative direction, or gradually decreases in the positive direction.

(b4) A lens which is disposed after, in an order from the object side to the image plane side, the sign of the abaxial chief ray height is reversed, should have at least one aspherical surface.

[0150] As regards correction of aberration by use of an aspherical surface, generally, an aspherical surface is introduced to a certain lens surface so as to reduce production of aberration at that surface (i.e., auxiliary introduction). An example is that, in a case of a convex single lens, since the spherical aberration is "under", an aspherical surface whose curvature becomes smaller in the peripheral portion is used to correct the spherical aberration.

[0151] In one preferred form of the present invention, as compared therewith, a three-group lens structure is basically used and, while reducing the number of lenses is aimed at on one hand, aspherical surfaces are introduced so as to cancel aberration in combination with other surfaces, to thereby accomplish good performance as well (i.e., positive introduction). By doing so, aberrations are corrected successfully.

[0152] More specifically, by satisfying the condition (b1) in the lens groups G1 and G2, a relation of cancelling two aspherical surface powers is defined. By this, it is assured that a change in refractive power applied to an arbitrary light from an object produces a refractive power change with which plural aberrations can be minimized simultaneously, which are not attainable with use of only spherical surfaces or a lens having only one aspherical surface.

[0153] Higher order aberrations which can not be easily corrected, such as distortion, curvature of field, astigmatism, sagittal transverse aberration or meridional transverse aberration, in higher order regions, for example, can be well corrected by the function of the condition (b1) above.

[0154] Satisfying the condition (b2) above is particularly effective for correction of the object-side telecentricity and higher order distortion aberrations.

[0155] More specifically, in the present invention, the condition of equation (1) for making the power of a negative lens group G2 large, enables correction of astigmatism or curvature of image field which relates to the Petzval sum. However, it influences the balance of telecentricity on the object side because of higher order negative powers, and higher order "under" distortion aberration is produced. When the condition (b2) is satisfied, the object-side telecentricity is well accomplished again. Simultaneously, an "over" distortion aberration in an opposite direction is produced to cancel it. Thus, the correction can be done well.

[0156] Further, satisfying condition (b3) is effective to mainly correct spherical aberration. This is because, in the positive third lens group G3 which bears the imaging function, "under" spherical aberration is produced. By satisfying condition (b3), "over" spherical aberration is positively produced by which the aberration correction is done successfully.

[0157] Satisfying condition (b4) is effective to mainly correct coma aberration and lower order distortion aberration. Across a stop, the sign of the height h_b of the chief ray is reversed. Before the stop (i.e., object side), use of an aspherical surface is effective for correction of lower light rays of the abaxial light, whereas, after the stop (image side), it is effective for correction of upper light rays. Thus, an aspherical surface is introduced into a lens after the stop, to thereby correct coma aberration satisfactorily.

[0158] Additionally, in a reduction projection system, lenses at the image side has a relatively large lens diameter for the sake of the numerical aperture, whereas it has a small image height. Thus, by using an aspherical surface, lower order distortion aberration is corrected.

[0159] The face of a aspherical surface lens opposite to its aspherical surface side may be a flat surface. This facilitates lens axial alignment during lens production, assembling and adjustment, and provides an advantage in respect to easy manufacture.

[0160] The face of a aspherical surface lens opposite to its aspherical surface side may be an aspherical surface. This expands the degree of freedom for aberration correction. Further, when the curvature change in these aspherical surfaces is set in the same direction, the influence of any eccentricity of the aspherical surface lens can be reduced.

[0161] As described, in a three-group type lens system according to one preferred form of the present invention, the power sharing is set appropriately in a lens structure having a smaller number of lenses, and an aspherical surface is provided at a suitable position. Also, an appropriate aspherical amount is set thereto, and the aspherical surface shape is determined to satisfy a predetermined condition or conditions. With this arrangement, distortion aberration, curvature of field, astigmatism, coma aberration and spherical aberration, for example, are well corrected while maintaining the dual-telecentricity. Thus, a projection optical system having a better optical performance is accomplished.

[0162] A five-group type lens system shown in the lens sectional view of Figure 53 comprises, in an order from the object side, a first lens group G1 having a positive refractive power, a second lens group G2 having a negative refractive power, a third lens group G3 having a positive refractive power, a fourth lens group G4 having a negative refractive power, and a fifth lens group G5 having a positive refractive power. An aspherical surface or surfaces are applied to suitable surfaces, by which good optical performance is provided. A stop is disposed between the fourth and fifth lens groups G4 and G5, or adjacent the fourth or fifth lens group G4 or G5.

[0163] Particularly, the whole lens system includes two negative lens groups, by which a strong negative refractive power required is distributed in the optical system. With this arrangement, the curvature of field can be corrected effectively and, also, an optical system having a short total length is accomplished.

[0164] Where five lens groups having positive and negative refractive powers are disposed alternately, if a larger numerical aperture and a higher resolution are attempted while all the lenses are formed with spherical surfaces, it inevitably results in an increase in the number of lenses used.

[0165] Thus, in the refractive power structure of the optical system shown in Figure 53, and in order to accomplish an optical system having a large numerical aperture and including a smaller number of lenses and being well aberration corrected, at least one aspherical surface is introduced into the optical system.

[0166] More specifically, in one preferred form of the present invention, a projection optical system of five-group type lens system, for projecting an image of an object upon an image plane, comprises, in an order from the object side, a first lens group G1 having a positive refractive power, a second lens group G2 having a negative refractive power, a third lens group G3 having a positive refractive power, a fourth lens group G4 having a negative refractive power, and a fifth lens group G5 having a positive refractive power, wherein, when h is a height of an axial marginal light ray and h_b is a height of a most abaxial chief ray, at least one aspherical surface is formed on a surface which satisfies a relation

$$|h_b/h| > 0.35 \quad (2)$$

wherein, when $\Delta ASPH$ is a largest aspherical amount of the aspherical surface from an optical axis to a lens effective diameter and L is an object-to-image distance, the aspherical surface satisfies a relation

$$|\Delta ASPH/L| > 1.0 \times 10^{-6} \quad (3)$$

[0167] The condition of equation (2) defines an appropriate surface for introduction of an aspherical surface. In conventional reduction projection optical systems, it is very difficult to satisfactorily correct distortion, curvature of image field, and astigmatism as well as transverse aberrations of meridional and sagittal, while maintaining the telecentricity.

[0168] This is because of the following reason. The telecentricity, distortion, curvature of image field, and astigmatism are all aberration amounts related to a principal ray passing through the center of a light flux. Although these aberrations depend on the placement and shape of lenses on the object side where, in the lens system as a whole, the height of the principal ray is high, practically it is very difficult to maintain, on one hand, the telecentricity with respect to principal rays from every object points on the object and, on the other hand, to refract the same principal ray so as to correct the distortion, the curvature of image field and the astigmatism.

[0169] Further, since on a lens surface those rays below the meridional are refracted at a height still higher than the principal ray, it is difficult to balance the meridional transverse aberration and aberration concerning these principal rays. Simultaneously, in order to correct the curvature of image field which has a tendency that it is "under" with higher image height, usually a concave lens is used to refract the light strongly. Then, however, the peripheral portion (sagittal halo) of the sagittal transverse aberration at high image heights further changes "over". Thus, it is difficult to balance them satisfactorily.

[0170] Enlarging the numerical aperture and widening the exposure area under these situations directly lead to further enlargement of the object side light flux and image height, and it amplifies the difficulties in aberration correction.

[0171] In a five-group type lens system according to one preferred form of the present invention, in consideration of the above, the condition of equation (2) is satisfied and an aspherical surface is formed on such surface having a large influence to abaxial principal rays, thereby to concentratedly and effectively correct the above-described aberrations to be improved. This effectively reduces the load for correction of other aberrations, and accomplishes a good optical performance.

[0172] If the lower limit of the condition of equation (2) is exceeded, the influence to axial marginal light rays increases, rather than to the abaxial principal rays, and therefore, the effect of correcting the aberrations to be improved diminishes. Thus, it becomes difficult to attain an enlarged numerical aperture and a wider exposure area.

[0173] In Figure 53, the condition of equation (2) is satisfied in a range from the object surface up to the lens groups G1, G2 and G3. Thus, at least one aspherical surface may be introduced to a surface in the range of lens groups G1, G2 and G3, satisfying the equation (2), by which better optical performance can be accomplished.

[0174] Particularly, if an aspherical surface is introduced into the lens group G1, since the height h_b becomes highest, it is very effective to control the distortion aberration coefficient.

[0175] Introducing an aspherical surface into the negative second lens group G2 is effective to control mainly the field curvature and astigmatism aberration coefficients. Since however it is in a cancelling relation with the first lens group G1 having a positive refractive power, the distortion aberration coefficient can also be controlled effectively.

[0176] The third lens group G3 has a large height h , and using an aspherical surface contributes the spherical aberration coefficient or the coma aberration coefficient. Therefore, introducing an aspherical surface there is effective for correction of spherical aberration or coma aberration.

[0177] While the optical function in relation to introduction of an aspherical surface has been described above, in order to obtain much better imaging performance as a result of introduction of an aspherical surface, the condition as defined by equation (3) should preferably be satisfied.

[0178] Equation (3) defines a condition concerning the aspherical amount. If the lower limit of condition (3) is exceeded, the effect of aspherical surface does not function well even though the aspherical surface is used in design to obtain a good imaging performance.

[0179] For example, if the conjugate distance is 1000 mm and the wavelength used is 193 nm, from equation (2), $\Delta ASPH$ is equal to 0.001 mm which corresponds to about ten Newton's rings. This is a sufficiently large value as an aspherical surface to be used in a projection optical system.

[0180] Further, for more effective use of an aspherical surface, at least one aspherical surface which satisfies the following relation may preferably be used:

$$|\Delta ASPH|/L > 1 \times 10^{-5} \quad (3b)$$

[0181] Further, in one preferred form of the present invention, when L is an object-to-image distance of said projection optical system and $\Sigma \phi_0$ is the sum of powers of the negative lens groups, the following relation is preferably satisfied:

$$|L \times \Sigma \phi_0| > 17$$

[0182] Generally, if the conjugate distance (object-to-image distance) L becomes longer, the total power Σ becomes smaller. If on the other hand the conjugate distance becomes shorter, the total power Σ becomes larger.

[0183] In one preferred form of the present invention, the product of the conjugate distance and the total power is

set to be not less than 17. The total power of the negative refractive power lens group is therefore made larger, mainly for satisfactory correction of the curvature of image field and the astigmatism. If the lower limit of this condition is exceeded, the Petzval sum increases in the positive direction, such that satisfactory correction of the curvature of image field or astigmatism becomes difficult to accomplish.

5 [0184] Further, conditions as defined by equations (1a), (2a) and (3a) may preferably be satisfied, for better correction of aberrations.

[0185] If the upper limit of the condition of equation (2a) is exceeded, lenses become too close to the object plane and the working distance can not be kept. If the magnification of the projection optical system is extraordinarily small, the working distance may be kept even though the condition is exceeded. However, an optical system having such a
10 extraordinarily small magnification is not practical for use in lithography.

[0186] When the upper limit of the condition of equation (3a) is exceeded, the aspherical amount becomes too large, causing a large increase in the time necessary for lens machining. Further, higher order aberrations produced at the aspherical surface become strong, which makes the satisfactory correction of aberration very difficult.

[0187] If the upper limit of the condition of equation (1a) is exceeded, the power of a negative lens group or groups
15 having a negative refractive power becomes too strong. Therefore, the Petzval sum is over-corrected, and it becomes difficult to mainly correct the curvature of image field and astigmatism, satisfactorily.

[0188] Further, the lens diameter of a positive lens group having a positive refractive power becomes larger, or the number of lenses increases.

[0189] In a five-group type lens system, at least one of the following conditions may preferably be satisfied. This
20 improves the effect of using an aspherical surface, and accomplishes a better aberration correction.

(c1) There should be at least two aspherical surfaces formed on surfaces satisfying the conditions of equations (2) and (3), and they should include regions in which, from a central portion to a peripheral portion of the surface, their
25 local curvature powers change with mutually opposite signs.

(c2) At least one of aspherical surfaces satisfying conditions (2) and (3) and being provided in a negative lens group should include a region in which, from a central portion to a peripheral portion of the surface, the local curvature
30 power thereof gradually increases in the negative direction.

(c3) At least one of aspherical surfaces provided in a positive lens group should include a region in which, from a central portion to a peripheral portion of the surface, the local curvature power thereof gradually increases in the
positive direction.

[0190] As regards correction of aberration by use of an aspherical surface, generally, there are two ways. One is that an aspherical surface is introduced to a certain lens surface so as to reduce production of aberration at that surface (auxiliary introduction). The other is that an aspherical surface is introduced so as to cancel an aberration in the relationship with other surfaces (positive introduction). The present invention is fundamentally based on the latter, and aberrations are well corrected thereby.
35

[0191] By establishing a cancelling relation between local powers of two aspherical surfaces while satisfying the condition (c1) above, it becomes easy to produce a change in refractive power such that plural aberrations can be minimized simultaneously.

40 [0192] Particularly, higher order aberrations which can not be easily corrected, such as distortion, curvature of field, astigmatism, sagittal transverse aberration or meridional transverse aberration, in higher order regions, for example, can be well corrected by the function of the condition (c1) above.

[0193] More preferably, two aspherical surfaces satisfying the condition (c1) may be provided in one of the lens groups G1 and G2. Alternatively, these two aspherical surfaces may be introduced into the lens groups G1 and G2,
45 respectively. This is preferable for better performance.

[0194] By introducing aspherical surfaces of the above-described condition into the one or both of the lens groups G1 and G2, mainly distortion aberration and image plane can be corrected effectively.

[0195] Satisfying the condition (c2) is particularly effective for correction of curvature of field and meridional and sagittal transverse aberrations.

50 [0196] This is because, if the Petzval sum is well corrected, it is still difficult to correct field curvature of large image height, particularly, sagittal field curvature having a tendency of "under" and, therefore, as described, it is difficult to balance it with the meridional or sagittal transverse aberrations.

[0197] In one preferred form of the present invention, by introducing an aspherical surface satisfying the condition (c2), the power in the negative refractive power direction of the peripheral portion is made large, without excessively
55 enlarging the paraxial power. As a result, the "under" portion of the field curvature is corrected toward the "over" side.

[0198] This provides an additional advantage that the degree of freedom for correction of aberrations at surfaces other than the aspherical surface can be expanded significantly, such that meridional or sagittal transverse aberrations and distortion aberrations, for example, can be corrected very well.

[0199] More preferably, one or more aspherical surfaces satisfying the condition (c2) may be provided in the lens group G1 or G2. This is desirable for better performance. By introducing an aspherical surface into one of or both of the lens groups G1 and G2, mainly distortion aberration and image plane can be corrected effectively.

[0200] The provision of an aspherical surface having a region, as defined in condition (c3), in which, from central portion to a peripheral portion of the surface, the local curvature power thereof gradually increases in the positive direction, is desirable for further improvement of performance.

[0201] Use of an aspherical surface such as described above, is effective mainly for correction of the object-side telecentricity and higher order distortion aberration.

[0202] In the example described above, of the lens system having five lens groups, the power of the two lens groups having a strong negative refractive power is enlarged to enable correction of astigmatism or curvature of image field which relates to the Petzval sum. However, it influences the balance of telecentricity on the object side because of higher order negative powers, and higher order "under" distortion aberration is produced.

[0203] In consideration of it, the object-side telecentricity is well accomplished again and, simultaneously, an "over" distortion aberration in an opposite direction is produced to cancel it. Thus, the correction can be done well.

[0204] As described above, with the provision of an aspherical surface which satisfies at least one of the conditions (c1) and (c2), an optical system having a high resolution and being well aberration-corrected can be accomplished. Further, the provision of an aspherical surface satisfying the condition (c3) is effective to provide an optical system of better performance.

[0205] Of course, plural aspherical surfaces may be introduced, by which better aberration correction is attained through the whole lens system. When an aspherical surface having a region in which, from a central portion to a peripheral portion of the surface, the local curvature power thereof decreases in the same direction, is introduced into a lens group of positive refractive power wherein the height of the axial marginal light ray is high, that is, the lens group G3 or G5, successful correction of spherical aberration or coma aberration is attainable.

[0206] In one preferred form of the present invention, the stop may be disposed in the fourth lens group G4 or the fifth lens group G5. It may be disposed in a lens group or between lens groups.

[0207] As regards a aspherical surface lens, the face thereof on the opposite side of its aspherical surface may not always be spherical. If that face comprises a plane surface, the production and assembling operation of such aspherical surface element becomes easier. This is particularly effective where an aspherical surface is to be formed on a lens having a large effective diameter. Some of all aspherical surface lenses used in a projection optical system may have a flat surface at the face on the opposite side of its aspherical surface. Further, all the aspherical surface lenses may have a flat surface at the face on the opposite side of the aspherical surface.

[0208] The face of an aspherical surface lens on the side opposite to its aspherical surface may be formed into an aspherical surface. Namely, a bi-aspherical surface lens may be used. In that occasion, all the aspherical surface lenses in a projection optical system may comprise bi-aspherical surface lenses, or only some of them may comprise bi-aspherical surface lenses.

[0209] In the refractive power arrangement of a seven-group type lens system of a projection optical system shown in Figure 54, at least one aspherical surface which satisfies the condition (3) is introduced to a surface within the optical system, so as to accomplish an optical system wherein aberrations are well corrected without excessively increasing the number of element lenses.

[0210] Equation (3) defines a condition for effective use of an aspherical surface. With the introduction of at least one aspherical surface satisfying this condition, the effect of using an aspherical surface well functions, and aberrations are corrected successfully.

[0211] If the condition (3) is not satisfied, aberration correction becomes difficult unless the number of lenses is made larger.

[0212] For example, if the object-to-image distance is 1000 mm and the wavelength used is 193 nm, from equation (3), the aspherical amount $\Delta ASPH$ becomes equal to 0.001 mm which corresponds to about ten Newton's rings. This is a sufficiently large value as an aspherical surface to be used in a projection optical system.

[0213] Further, for more effective use of an aspherical surface in a projection optical system of seven-group structure, the condition (3) should preferably be change to:

$$|\Delta ASPH/LI| > 1 \times 10^{-5} \quad (3a)$$

[0214] The projection optical system shown in Figure 54 comprises, from the first lens surface at the object side to the stop plane, a first lens group L1 having a positive refractive power, a second lens group L2 having a negative refractive power, a third lens group L3 having a positive refractive power, a fourth lens group L4 having a negative refractive power, a fifth lens group L5 having a positive refractive power, and a sixth lens group L6 having a negative refractive power.

[0215] Within this range near the object, the height of the abaxial light ray is high, and the axial light ray is low. Also,

adjacent the stop, the height of the abaxial light ray becomes lower, while the axial light ray becomes higher than that at adjacent the object surface.

[0216] Thus, before the stop and in the vicinity of the stop, the relation between the height of the principal ray and the height of the axial light ray largely changes. Particularly, accomplishing a large numerical aperture means that, near the object, the numerical aperture light becomes wider.

[0217] In consideration of it, before the stop, particularly the production of abaxial aberrations such as distortion aberration, astigmatism, comma aberrations should be made small as much as possible. If this is not attained, the axial aberrations and abaxial aberrations are not balanced, and the aberration correction for an optical system becomes very difficult. Therefore, preferably, at least one aspherical surface set within the range as defined by equation (3) should be introduced, by which abaxial aberrations such as distortion aberration, astigmatism, comma aberrations can be corrected effectively.

[0218] The stop may be disposed in or adjacent the sixth lens group L6, or in or adjacent the fifth lens group L5.

[0219] In the seven-group structure described above, at least one aspherical surface may preferably be provided between the first lens, at the object side, to the position of the stop.

[0220] Further, in the seven-group structure, when h is a height of an axial marginal light ray and h_b is a height of a most abaxial chief ray, at least one aspherical surface may preferably be formed on a surface which satisfies a relation

$$|h_b/h| > 0.35 \quad (2)$$

[0221] In conventional reduction projection optical systems, it is very difficult to satisfactorily correct distortion, curvature of image field, and astigmatism as well as transverse aberrations of meridional and sagittal, while maintaining the telecentricity.

[0222] This is because of the following reason. The telecentricity, distortion, curvature of image field, and astigmatism are all aberration amounts related to a principal ray passing through the center of a light flux. Although these aberrations depend on the placement and shape of lenses on the object side where, in the lens system as a whole, the height of the principal ray is high, practically it is very difficult to maintain, on one hand, the telecentricity with respect to principal rays from every object points on the object and, on the other hand, to refract the same principal ray so as to correct the distortion, the curvature of image field and the astigmatism.

[0223] Further, since on a lens surface those rays below the meridional are refracted at a height still higher than the principal ray, it is difficult to balance the meridional transverse aberration and aberration concerning these principal rays. Simultaneously, in order to correct the curvature of image field which has a tendency that it is "under" with higher image height, usually a concave lens is used to refract the light strongly. Then, however, the peripheral portion of the sagittal transverse aberration at high image heights further changes "over". Thus, it is difficult to balance them satisfactorily.

[0224] Enlarging the numerical aperture and widening the exposure area under these situations directly lead to further enlargement of the object side light flux and image height, and it amplifies the difficulties in aberration correction.

[0225] In a projection optical system of seven-group structure according to one preferred form of the present invention, in consideration of the above, the condition of equation (2) is satisfied and an aspherical surface is formed on such surface having a large influence to abaxial principal rays, thereby to concentratedly and effectively correct the above-described aberrations to be improved. This effectively reduces the load for correction of other aberrations, and accomplishes a good optical performance.

[0226] If the lower limit of the condition of equation (2) is exceeded, the influence to axial marginal light rays increases, rather than to the abaxial principal rays, and therefore, the effect of correcting the aberrations to be improved diminishes. Thus, it becomes difficult to attain an enlarged numerical aperture and a wider exposure area.

[0227] In Figure 54, condition (2) is satisfied in a range from the object surface to the lens groups G1 - G4. Thus, introducing at least one aspherical surface into this range is a condition for better optical performance.

[0228] Particularly, when an aspherical surface is introduced into the lens group G1, since the height h_b of the abaxial chief ray is highest, it is very effective to control the distortion aberration coefficient.

[0229] Introducing an aspherical surface into the lens group G2 having a negative refractive power is effective to control mainly the field curvature and astigmatism aberration. Since however it is in a cancelling relation with the lens group G1 having a positive refractive power, the distortion aberration coefficient can also be controlled effectively. Since in the positive lens group G3, the height h of the axial light ray is high and using an aspherical surface contributes the spherical aberration coefficient or the comma aberration coefficient, an aspherical surface may well be introduced to this lens group, for better correction of spherical aberration or comma aberration.

[0230] In one preferred form of the present invention, when L is an object-to-image distance of said projection optical system and $\sum \phi$ is the sum of powers of the negative lens groups, a relation

$$|L \times \sum \phi| > 17$$

may preferably be satisfied.

[0231] Generally, if the conjugate distance (object-to-image distance) L becomes longer, the total power ϕ of the negative lens groups becomes smaller. If on the other hand the conjugate distance becomes shorter, the total power ϕ of the negative lens groups becomes larger.

[0232] In one preferred form of the present invention, the product of the conjugate distance and the total power is set to be not less than 17. The total power of the negative refractive power lens group is therefore made larger, mainly for satisfactory correction of the curvature of image field and the astigmatism. If the lower limit of the condition is exceeded, the Petzval sum increases in the positive direction, such that satisfactory correction of the curvature of image field or astigmatism becomes difficult to accomplish.

[0233] Further, also in the seven-group structure, conditions as defined by equations (1a), (2a) and (3a) described hereinbefore may preferably be satisfied, for better correction of aberrations.

[0234] If, for example, the upper limit of the condition of equation (3a) is exceeded, the aspherical amount becomes large, and the lens processing time becomes long. Further, large higher-order aberrations may be produced at the aspherical surface, which may make the aberration correction difficult.

[0235] If the upper limit of the condition of equation (2a) is exceeded, lenses become too close to the object plane and the working distance can not be kept. If the magnification of the projection optical system is extraordinarily small, the working distance may be kept even though the condition is exceeded. However, an optical system having such a extraordinarily small magnification is not practical for use in lithography.

[0236] If the upper limit of the condition of equation (1a) is exceeded, the power of a negative lens group or groups having a negative refractive power becomes too strong. Therefore, the Petzval sum is over-corrected, and it becomes difficult to mainly correct the curvature of image field and astigmatism, satisfactorily.

[0237] Further, the lens diameter of a positive lens group having a positive refractive power becomes larger, or the number of lenses increases.

[0238] In a seven-group type lens system, at least one of the following conditions may preferably be satisfied. This improves the effect of using an aspherical surface, and accomplishes a better aberration correction.

(d1) There should be at least two aspherical surfaces which include regions in which, from a central portion to a peripheral portion of the surface, their local curvature powers change with mutually opposite signs.

(d2) At least one of aspherical surfaces provided in a negative lens group should include a region in which, from a central portion to a peripheral portion of the surface, the local curvature power thereof gradually increases in the negative direction or gradually decreases in the positive direction.

(d3) At least one of aspherical surfaces provided in a positive lens group should include a region in which, from a central portion to a peripheral portion of the surface, the local curvature power thereof gradually increases in the positive direction or gradually decreases in the negative direction.

[0239] As regards correction of aberration by use of an aspherical surface, generally, there are two ways. One is that an aspherical surface is introduced to a certain lens surface so as to reduce production of aberration at that surface (auxiliary introduction). The other is that an aspherical surface is introduced so as to cancel an aberration in the relationship with other surfaces (positive introduction). The present invention is fundamentally based on the latter, and aberrations are well corrected thereby.

[0240] By establishing a cancelling relation between local powers of two aspherical surfaces while satisfying the condition (d1) above, it becomes easy to produce a change in refractive power such that plural aberrations can be minimized simultaneously.

[0241] Particularly, higher order aberrations which can not be easily corrected, such as distortion, curvature of field, astigmatism, sagittal transverse aberration or meridional transverse aberration, in higher order regions, for example, can be well corrected by the function of the condition (d1) above.

[0242] More preferably, two aspherical surfaces satisfying the condition (d1) may be provided in one of the lens groups G1 and G2. Alternatively, these two aspherical surfaces may be introduced into the lens groups G1 and G2, respectively. This is preferable for better performance.

[0243] By introducing aspherical surfaces of the above-described condition into the one or both of the lens groups G1 and G2, mainly distortion aberration and image plane can be corrected effectively.

[0244] Satisfying the condition (d2) is particularly effective for correction of curvature of field and meridional and sagittal transverse aberrations.

[0245] This is because, if the Petzval sum is well corrected, it is still difficult to correct field curvature of large image height, particularly, sagittal field curvature having a tendency of "under" and, therefore, as described, it is difficult to balance it with the meridional or sagittal transverse aberrations.

[0246] In one preferred form of the present invention, by introducing an aspherical surface satisfying the condition (d2), the power in the negative refractive power direction of the peripheral portion is made large, without excessively

enlarging the paraxial power. As a result, the "under" portion of the field curvature is corrected toward the "over" side.

[0247] This provides an additional advantage that the degree of freedom for correction of aberrations at surfaces other than the aspherical surface can be expanded significantly, such that meridional or sagittal transverse aberrations and distortion aberrations, for example, can be corrected very well.

5 [0248] More preferably, one or more aspherical surfaces satisfying the condition (d2) may be provided in the lens group G1 or G2. This is desirable for better performance. By introducing an aspherical surface into one of or both of the lens groups G1 and G2, mainly distortion aberration and image plane can be corrected effectively.

[0249] The provision of an aspherical surface having a region, as defined in condition (d3), in which, from central portion to a peripheral portion of the surface, the local curvature power thereof gradually increases in the positive direction, is desirable for further improvement of performance.

10 [0250] Use of an aspherical surface such as described above, is effective mainly for correction of the object-side telecentricity and higher order distortion aberration.

[0251] In the example described above, of the lens system having seven lens groups, the power of the three lens groups is enlarged to enable correction of astigmatism or curvature of image field which relates to the Petzval sum. However, it influences the balance of telecentricity on the object side because of higher order negative powers, and higher order "under" distortion aberration is produced.

[0252] In consideration of it, the object-side telecentricity is well accomplished again and, simultaneously, an "over" distortion aberration in an opposite direction is produced to cancel it. Thus, the correction can be done well.

[0253] As described above, with the provision of an aspherical surface which satisfies at least one of the conditions (d1) and (d2), an optical system having a high resolution and being well aberration-corrected can be accomplished. Further, the provision of an aspherical surface satisfying the condition (d3) is effective to provide an optical system of better performance.

20 [0254] Of course, plural aspherical surfaces may be introduced, in addition to the above-described aspherical surface, by which better aberration correction is attained through the whole lens system. When an aspherical surface having a region in which, from a central portion to a peripheral portion of the surface, the local curvature power thereof decreases in the same direction, is introduced into a lens group of positive refractive power wherein the height of the axial marginal light ray is high, that is, the lens group G5 or G7, successful correction of spherical aberration or comma aberration is attainable.

[0255] As regards a aspherical surface lens, the face thereof on the opposite side of its aspherical surface may not always be spherical. If that face comprises a plane surface, the production and assembling operation of such aspherical surface element becomes easier. This is particularly effective where an aspherical surface is to be formed on a lens having a large effective diameter. Some of all aspherical surface lenses used in a projection optical system may have a flat surface at the face on the opposite side of its aspherical surface. Further, all the aspherical surface lenses may have a flat surface at the face on the opposite side of the aspherical surface.

30 [0256] The face of an aspherical surface lens on the side opposite to its aspherical surface may be formed into an aspherical surface. Namely, a bi-aspherical surface lens may be used. In that occasion, all the aspherical surface lenses in a projection optical system may comprise bi-aspherical surface lenses, or only some of them may comprise bi-aspherical surface lenses.

[0257] Next, an example of aspherical surface processing method applicable to a projection optical system of the present invention will be described.

40 [0258] As regards a process for forming an aspherical surface lens which can meet a large diameter lens to be used in lithography or the like, an example is reported in "Computer-controlled polishing of telescope mirror segments", Robert A. Jones, OPTICAL ENGINEERING, Mar/Apr Vol.22, No.2, 1983. In this example, a three-dimensionally computer-controlled grinding machine is used to produce an aspherical surface shape and, thereafter, a computer-controlled polishing machine (CCP) is used to finish the same. A shape precision of 0.025 λ rms ($\lambda = 633$ nm) is reported.

45 [0259] Figure 88 is a schematic view for explaining a procedure for making an aspherical surface by mechanical processings. Denoted in the drawing at 501 is a substrate, and denoted at 502 is a substrate rotating mechanism. Denoted at 503 is a stage, and denoted at 504 is a spherical surface pad. Denoted at 505 is a spherical surface pad rotating mechanism, and denoted at 506 is a load controlling mechanism. Denoted at 507 is a polishing liquid supplying nozzle, and denoted at 508 is a polishing liquid. The substrate 501 is rotatably mounted on the stage 503 which is movable, and the substrate can be rotated by the rotating mechanism 502.

50 [0260] The contact pressure to the surface of the substrate 501 being rotated is controlled by the load controlling mechanism 506. The spherical surface pad 405 being rotated by the pad rotating mechanism 505 contacts the surface of the substrate. The polishing liquid 508 is supplied to the contact surface by the liquid supplying mechanism 507, by which the contact surface is polished.

55 [0261] The position of the stage 503 and the contact pressure of the spherical pad 504 as applied by the load controlling mechanism 506 are controlled by a computer, not shown. With this procedure, an aspherical surface lens can be produced. However, the aspherical surface processing method is not limited to this, and any other method is usable.

[0262] Important features of lens structures in numerical examples of projection optical systems according to the present invention, will now be described.

[Example 1]

[0263] Figure 1 is a lens sectional view of a projection optical system according to Numerical Example 1 of the present invention. The projection optical system has a reference wavelength 193 nm, a numerical aperture $NA = 0.65$, a projection magnification $\beta = 1:4$, a lens conjugate distance $L = 1000$ mm, and an exposure region of diameter $\varnothing 27.3$ mm. This optical system is accomplished by lenses of a small number 17 (seventeen). It uses six aspherical surfaces.

[0264] Table 1 shows specifications of this example, in regard to the conditions. Figure 2 illustrates changes in power of aspherical surfaces, wherein the axis of ordinate represents the height of aspherical surface from the optical axis, being standardized with respect to the effective diameter, and the axis of abscissa denotes the aspherical surface number. The leftward and rightward directions correspond to negative and positive directions of the change in local curvature power, respectively. Figure 3 illustrates aberrations of this example.

[0265] In Numerical Example 1, surfaces r1 - r8 belong to a positive first lens group G1, all of which are spherical surfaces. Surfaces r9 - r16 belong to a negative second lens group G2, wherein r10 and r12 are aspherical surfaces. Surfaces r17 - r34 belong to a positive third lens group G3, wherein r20, r23, r25 and r33 are aspherical surfaces.

[0266] In this example, as shown in Table 1, first the condition of equation (1) for correction of the Petzval sum is satisfied. Then, as aspherical surfaces satisfying the conditions of equations (2) and (3), two aspherical surfaces are placed in the second group. With this arrangement, the telecentricity, distortion aberration and curvature of field, for example, are corrected well.

[0267] The first lens group is provided by one negative lens and three positive lenses.

[0268] The second lens group is provided by four negative lenses. The aspherical surfaces at r10 and r12 include regions in which the local curvature powers change with mutually opposite signs so as to cancel each other, for correction of field curvature and distortion, for example. Thus, the functions as defined by conditions (a1) and (a2) described above are satisfied.

[0269] The third lens group is provided by eight positive lenses and one negative lens. Five of eight positive lenses are made of fluorite ($n = 1.5014$), for correction of chromatic aberration. In the aspherical surfaces at r20, r23 and r25, the local curvature power changes in the negative direction so as mainly to correct the spherical aberration. The aspherical surface at r33 serves mainly to correct lower orders of the distortion aberration. The local curvature power thereof changes in the positive direction.

[0270] In the lens system, a pair of lenses, comprising a negative meniscus lens having its concave surface facing to the image plane side and a positive lens having a first concave surface facing to the image plane side, are disposed, to assist correction of field curvature, comma aberration and distortion aberration.

[0271] With this arrangement, aberrations are corrected satisfactorily, as illustrated in Figure 3.

[Example 2]

[0272] Figure 4 is a lens sectional view of a projection optical system according to Numerical Example 2 of the present invention. The projection optical system has a reference wavelength 193 nm, a numerical aperture $NA = 0.65$, a projection magnification $\beta = 1:4$, a lens conjugate distance $L = 1000$ mm, and an exposure region of diameter $\varnothing 27.3$ mm. This optical system is accomplished by lenses of a small number 17 (seventeen). It uses nine aspherical surfaces.

[0273] Table 2 shows specifications of this example, in regard to the conditions. Figure 5 illustrates changes in power of aspherical surfaces, wherein the axis of ordinate represents the height of aspherical surface from the optical axis, being standardized with respect to the effective diameter, and the axis of abscissa denotes the aspherical surface number. The leftward and rightward directions correspond to negative and positive directions of the change in local curvature power, respectively. Figure 6 illustrates aberrations of this example.

[0274] In Numerical Example 2, surfaces r1 - r10 belong to a positive first lens group G1, wherein r2 and r5 are aspherical surfaces. Surfaces r11 - r16 belong to a negative second lens group G2, wherein r11 and r15 are aspherical surfaces. Surfaces r17 - r34 belong to a positive third lens group G3, wherein r20, r23, r27, r32 and r33 are aspherical surfaces.

[0275] In each of the lenses having aspherical surfaces r2, r5, r15, r23, r32 and r33, the face on the side opposite to its aspherical surface is a plane surface.

[0276] In this example, as shown in Table 2, first the condition of equation (1) for correction of the Petzval sum is satisfied. Then, as aspherical surfaces satisfying the conditions of equations (2) and (3), four aspherical surface are used. Namely, two aspherical surfaces are placed in the first lens group, and two aspherical surfaces are placed in the second lens group. With this arrangement, the telecentricity, distortion aberration and curvature of field, for example, are corrected well.

[0277] The first lens group is provided by one negative lens and four positive lenses. The aspherical surfaces at r2 and r5 include regions in which their local curvature powers gradually change in the positive direction. Thus, the function as defined by condition (a3) described above is satisfied.

[0278] The second lens group is provided by three negative lenses. In the central portion of the surface at r11 and in the surface at r15, the local curvature power changes in the negative direction, and the function of condition (a2) is satisfied. The aspherical surfaces at r11 and r15 include regions, at peripheral portions, in which the local curvature powers change with mutually opposite signs so as to cancel each other, for correction of higher orders of field curvature and distortion, for example. Thus, the function as defined by condition (a1) described above is satisfied.

[0279] Additionally, at the central portion of the surface r11, at the surface r15, at the central portion of the surface r2 of the first lens group G1, and at the surface r5, there are regions in which the local curvature powers change with mutually opposite signs. Thus, also in this respect, the function of condition (a1) is satisfied. This is effective for correction of the telecentricity and distortion, for example.

[0280] The third lens group is provided by seven positive lenses and two negative lenses. Five of eight positive lenses are made of fluorite ($n = 1.5014$), for correction of chromatic aberration. In the aspherical surfaces at r20, r23 and r27, the local curvature power changes in the negative direction so as mainly to correct the spherical aberration. The aspherical surfaces at r32 and r33 include regions in which the local curvature powers change in the positive direction, mainly for correction of distortion.

[0281] With this arrangement, aberrations are corrected satisfactorily, as illustrated in Figure 6.

[Example 3]

[0282] Figure 7 is a lens sectional view of a projection optical system according to Numerical Example 3 of the present invention. The projection optical system has a reference wavelength 193 nm, a numerical aperture $NA = 0.65$, a projection magnification $\beta = 1:4$, a lens conjugate distance $L = 000$ mm, and an exposure region of diameter $\varnothing 27.3$ mm. This optical system is accomplished by lenses of a small number 17 (seventeen). It uses seven aspherical surfaces.

[0283] Table 3 shows specifications of this example, in regard to the conditions. Figure 8 illustrates changes in power of aspherical surfaces, wherein the axis of ordinate represents the height of aspherical surface from the optical axis, being standardized with respect to the effective diameter, and the axis of abscissa denotes the aspherical surface number. The leftward and rightward directions correspond to negative and positive directions of the change in local curvature power, respectively. Figure 9 illustrates aberrations of this example.

[0284] In Numerical Example 3, surfaces r1 - r8 belong to a positive first lens group G1, wherein r2 and r7 are aspherical surfaces. Surfaces r9 - r16 belong to a negative second lens group G2, wherein r12 is an aspherical surface. Surfaces r17 - r34 belong to a positive third lens group G3, wherein r20, r23, r25 and r33 are aspherical surfaces.

[0285] In each aspherical lenses having aspherical surfaces, the face on the side opposite to its aspherical surface is a plane surface.

[0286] In this example, as shown in Table 3, first the condition of equation (1) for correction of the Petzval sum is satisfied. Then, as aspherical surfaces satisfying the conditions of equations (2) and (3), three aspherical surface are used. Namely, two aspherical surfaces are placed in the first lens group, and one aspherical surface is placed in the second lens group. With this arrangement, the telecentricity, distortion aberration and curvature of field, for example, are corrected well.

[0287] The first lens group is provided by one negative lens and three positive lenses. In the aspherical surface at r7, the local curvature power gradually changes in the positive direction, thus satisfying the function defined by condition (a3) described above. Simultaneously, in relation to the central portion of the aspherical surface at r2, their local curvature powers change with mutually opposite signs to cancel with each other. Thus, the function as defined by condition (a1) described above is satisfied.

[0288] The second lens group is provided by four negative lenses. Two lenses at the image plane side have a large power for correction of the Petzval sum. In order to cancel it, in the central portion of the surface at r12, the local curvature power changes in the positive direction. At the peripheral portion, however, the local curvature power changes in the negative direction, for correction of higher order field curvature. Thus, the function of condition (a2) is satisfied.

[0289] Additionally, at this peripheral portion and the aspherical surface r7 of the first lens group G1, the local curvature powers change with mutually opposite signs to cancel with each other. Thus, also the function of condition (a1) is satisfied.

[0290] The third lens group is provided by eight positive lenses and one negative lens. In the aspherical surfaces at r20, r23 and r25, the local curvature power changes in the negative direction so as mainly to correct the spherical aberration. The aspherical surface at r33 serves mainly to correct distortion, and the local curvature power thereof changes in the positive direction, mainly for correction of distortion.

[0291] In the lens system, a pair of lenses, comprising a negative meniscus lens having its concave surface facing

to the image plane side and a positive lens having a first concave surface facing to the image plane side, are disposed, to assist correction of field curvature, comma aberration and distortion aberration.

[0292] With this arrangement, aberrations are corrected satisfactorily, as illustrated in Figure 9.

[Example 4]

[0293] Figure 10 is a lens sectional view of a projection optical system according to Numerical Example 4 of the present invention. The projection optical system has a reference wavelength 193 nm, a numerical aperture $NA = 0.65$, a projection magnification $\beta = 1:4$, a lens conjugate distance $L = 1000$ mm, and an exposure region of diameter $\varnothing 27.3$ mm. This optical system is accomplished by lenses of a small number 15 (fifteen). It uses eight aspherical surfaces.

[0294] Table 4 shows specifications of this example, in regard to the conditions. Figure 11 illustrates changes in power of aspherical surfaces, wherein the axis of ordinate represents the height of aspherical surface from the optical axis, being standardized with respect to the effective diameter, and the axis of abscissa denotes the aspherical surface number. The leftward and rightward directions correspond to negative and positive directions of the change in local curvature power, respectively. Figure 12 illustrates aberrations of this example.

[0295] In Numerical Example 4, surfaces r1 - r8 belong to a positive first lens group G1, wherein r7 and r8 are aspherical surfaces. Surfaces r9 - r14 belong to a negative second lens group G2, wherein r9 and r10 are aspherical surfaces. Surfaces r15 - r30 belong to a positive third lens group G3, wherein r18, r23, r29 and r30 are aspherical surfaces.

[0296] Each of the lenses having surfaces r7 and r8; r9 and r10; and r29 and r30 is a bi-aspherical surface lens having aspherical surfaces on both sides thereof.

[0297] In this example, as shown in Table 4, first the condition of equation (1) for correction of the Petzval sum is satisfied. Then, as aspherical surfaces satisfying the conditions of equations (2) and (3), four aspherical surface are used. Namely, two aspherical surfaces are placed in the first lens group, and two aspherical surface is placed in the second lens group. With this arrangement, the telecentricity, distortion aberration and curvature of field, for example, are corrected well.

[0298] The first lens group is provided by one negative lens and three positive lenses. In the aspherical surfaces at r7 and r8 which are the surfaces of a bi-aspherical surface lens, their local curvature powers change with mutually opposite signs to cancel with each other, thus satisfying the function defined by condition (a1) described above and, simultaneously, the function of condition (a3) described above.

[0299] The second lens group is provided by three negative lenses. At the aspherical surfaces r9 and r10 which are the surfaces of a bi-aspherical surface lens, the local curvature powers change with mutually opposite signs to cancel with each other. Thus, the function of condition (a1) is satisfied and, simultaneously, the function of condition (a2) is satisfied.

[0300] Similarly, in the relation between the surfaces r8 and r9, and between the surfaces r7 and r10, the function defined by condition (a1) is satisfied. Thus, through mutual cancellation, the telecentricity, distortion and field curvature, for example, are well corrected.

[0301] The third lens group is provided by seven positive lenses and one negative lens. In the aspherical surfaces at r18 and r23, the local curvature power changes in the negative direction so as mainly to correct the spherical aberration. In the aspherical surface at r29, the local curvature power thereof at the peripheral portion changes in the positive direction, mainly for correction of distortion.

[0302] In the lens system, a pair of lenses, comprising a negative lens having a second concave surface facing to the image plane side and a positive meniscus lens having its first concave surface facing to the image plane side, are disposed, to assist correction of field curvature, comma aberration and distortion aberration.

[0303] With this arrangement, aberrations are corrected satisfactorily, as illustrated in Figure 12.

[Example 5]

[0304] Figure 13 is a lens sectional view of a projection optical system according to Numerical Example 5 of the present invention. The projection optical system has a reference wavelength 193 nm, a numerical aperture $NA = 0.65$, a projection magnification $\beta = 1:4$, a lens conjugate distance $L = 1000$ mm, and an exposure region of diameter $\varnothing 27.3$ mm. This optical system is accomplished by lenses of a very small number 14 (fourteen). It uses ten aspherical surfaces.

[0305] Table 5 shows specifications of this example, in regard to the conditions. Figure 14 illustrates changes in power of aspherical surfaces, wherein the axis of ordinate represents the height of aspherical surface from the optical axis, being standardized with respect to the effective diameter, and the axis of abscissa denotes the aspherical surface number. The leftward and rightward directions correspond to negative and positive directions of the change in local curvature power, respectively. Figure 15 illustrates aberrations of this example.

[0306] In Numerical Example 5, surfaces r1 - r8 belong to a positive first lens group G1, wherein r7 and r8 are aspherical surfaces. Surfaces r9 - r14 belong to a negative second lens group G2, wherein r9 and r10 are aspherical surfaces. Surfaces r15 - r28 belong to a positive third lens group G3, wherein r17, r18, r21, r22, r27 and r28 are aspherical surfaces.

5 [0307] Each of the aspherical lenses having aspherical surfaces is a bi-aspherical surface lens having aspherical surfaces on both sides thereof.

[0308] In this example, as shown in Table 5, first the condition of equation (1) for correction of the Petzval sum is satisfied. Then, as aspherical surfaces satisfying the conditions of equations (2) and (3), four aspherical surface are used. Namely, two aspherical surfaces are placed in the first lens group, and two aspherical surface is placed in the second lens group. With this arrangement, the telecentricity, distortion aberration and curvature of field, for example, are corrected well.

[0309] The first lens group is provided by one negative lens and three positive lenses. In the aspherical surfaces at r7 and r8 which are the surfaces of a bi-aspherical surface lens, their local curvature powers change with mutually opposite signs to cancel with each other, thus satisfying the function defined by condition (a1) described above and, simultaneously, the function of condition (a3) described above.

15 [0310] The second lens group is provided by three negative lenses. At the aspherical surfaces r9 and r10 which are the surfaces of a bi-aspherical surface lens, the local curvature powers change with mutually opposite signs to cancel with each other. Thus, the function of condition (a1) is satisfied and, simultaneously, the function of condition (a2) is satisfied.

20 [0311] Similarly, in the relation between the surfaces r8 and r9, and between the surfaces r7 and r10, the function defined by condition (a1) is satisfied. Thus, through mutual cancellation, the telecentricity, distortion and field curvature, for example, are well corrected.

[0312] The third lens group is provided by six positive lenses and one negative lens. In the aspherical surfaces at r18, r21 and r22, the local curvature power changes in the negative direction so as mainly to correct the spherical aberration. In the aspherical surface at r27, the local curvature power thereof at the peripheral portion changes in the positive direction, for correction of distortion, for example.

25 [0313] In the lens system, a pair of lenses, comprising a negative meniscus lens having a concave surface facing to the image plane side and a positive lens having its first concave surface facing to the image plane side, are disposed, to assist correction of field curvature, comma aberration and distortion aberration.

30 [0314] With this arrangement, aberrations are corrected satisfactorily, as illustrated in Figure 15.

[Example 6]

35 [0315] Figure 16 is a lens sectional view of a projection optical system according to Numerical Example 6 of the present invention. The projection optical system has a reference wavelength 248 nm, a numerical aperture NA = 0.65, a projection magnification $\beta = 1:4$, a lens conjugate distance $L = 1050$ mm, and an exposure region of diameter $\varnothing 27.3$ mm. This optical system is accomplished by lenses of a number 27 (twenty-seven). It uses two aspherical surfaces.

[0316] Table 6 shows specifications of this example, in regard to the conditions. Figure 17 illustrates changes in power of aspherical surfaces, wherein the axis of ordinate represents the height of aspherical surface from the optical axis, being standardized with respect to the effective diameter, and the axis of abscissa denotes the aspherical surface number. The leftward and rightward directions correspond to negative and positive directions of the change in local curvature power, respectively. Figure 18 illustrates aberrations of this example.

40 [0317] In Numerical Example 6, surfaces r1 - r6 belong to a positive first lens group G1, all of which are spherical surfaces. Surfaces r7 - r16 belong to a negative second lens group G2, wherein r13 is an aspherical surface. Surfaces r17 - r26 belong to a positive third lens group G3, all of which are spherical surfaces. Surfaces r27 - r34 belong to a negative fourth lens group G4, all of which are spherical surfaces. Surfaces r35 - r54 belong to a positive fifth lens group G5, wherein r53 is an aspherical surface.

[0318] In this example, as shown in Table 6, first the condition of equation (1) for correction of the Petzval sum is satisfied. Then, as aspherical surfaces satisfying the conditions of equations (2) and (3), one aspherical surface is placed in the first lens group. With this arrangement, the telecentricity, distortion aberration and curvature of field, for example, are corrected well.

[0319] The first lens group is provided by three positive lenses, mainly for correction of telecentricity and distortion.

[0320] The second lens group is provided by five negative lenses. At the aspherical surface r13, the local curvature power changes in the negative direction, thus satisfying the function defined by condition (a2). Also, distortion, for example, is corrected in the relationship with the first lens group.

55 [0321] The third lens group is provided by five positive lenses.

[0322] The fourth lens group is provided by four negative lenses, and they function mainly to correct the Petzval sum.

[0323] The fifth lens group is provided by eight positive lenses and two negative lenses.

[0324] With this arrangement, aberrations are corrected satisfactorily, as illustrated in Figure 18.

[Example 7]

[0325] Figure 19 is a lens sectional view of a projection optical system according to Numerical Example 7 of the present invention. The projection optical system has a reference wavelength 248 nm, a numerical aperture $NA = 0.65$, a projection magnification $\beta = 1:4$, a lens conjugate distance $L = 1050$ mm, and an exposure region of diameter $\varnothing 27.3$ mm. This optical system is accomplished by lenses of a number 27 (twenty-seven). It uses two aspherical surfaces.

[0326] Table 7 shows specifications of this example, in regard to the conditions. Figure 20 illustrates changes in power of aspherical surfaces, wherein the axis of ordinate represents the height of aspherical surface from the optical axis, being standardized with respect to the effective diameter, and the axis of abscissa denotes the aspherical surface number. The leftward and rightward directions correspond to negative and positive directions of the change in local curvature power, respectively. Figure 21 illustrates aberrations of this example.

[0327] In Numerical Example 7, surfaces $r1 - r6$ belong to a positive first lens group $G1$, all of which are spherical surfaces. Surfaces $r7 - r14$ belong to a negative second lens group $G2$, wherein $r10$ and $r11$ are aspherical surfaces. Surfaces $r15 - r24$ belong to a positive third lens group $G3$, all of which are spherical surfaces. Surfaces $r25 - r32$ belong to a negative fourth lens group $G4$, all of which are spherical surfaces. Surfaces $r33 - r54$ belong to a positive fifth lens group $G5$, all of which are spherical surface.

[0328] In this example, as shown in Table 7, first the condition of equation (1) for correction of the Petzval sum is satisfied. Then, as aspherical surfaces satisfying the conditions of equations (2) and (3), two aspherical surface are placed in the second lens group. With this arrangement, the telecentricity, distortion aberration and curvature of field, for example, are corrected well.

[0329] The first lens group is provided by three positive lenses, mainly for correction of telecentricity and distortion.

[0330] The second lens group is provided by four negative lenses. The aspherical surfaces at $r10$ and $r11$ include regions in which their local curvature powers change with mutually opposite signs. Thus, the function defined by condition (a1) as well as the function of condition (a2) are satisfied.

[0331] The third lens group is provided by five positive lenses.

[0332] The fourth lens group is provided by four negative lenses, and they function mainly to correct the Petzval sum.

[0333] The fifth lens group is provided by nine positive lenses and two negative lenses.

[0334] With this arrangement, aberrations are corrected satisfactorily, as illustrated in Figure 21.

[Example 8]

[0335] Figure 22 is a lens sectional view of a projection optical system according to Numerical Example 8 of the present invention. The projection optical system has a reference wavelength 248 nm, a numerical aperture $NA = 0.65$, a projection magnification $\beta = 1:4$, a lens conjugate distance $L = 1050$ mm, and an exposure region of diameter $\varnothing 27.3$ mm. This optical system is accomplished by lenses of a number 24 (twenty-four) which is relatively small as a five-group type lens system. It uses seven aspherical surfaces, four of which are aspherical surfaces of two bi-aspherical lenses each having two aspherical surfaces on both sides thereof.

[0336] Table 8 shows specifications of this example, in regard to the conditions. Figure 23 illustrates changes in power of aspherical surfaces, wherein the axis of ordinate represents the height of aspherical surface from the optical axis, being standardized with respect to the effective diameter, and the axis of abscissa denotes the aspherical surface number. The leftward and rightward directions correspond to negative and positive directions of the change in local curvature power, respectively. Figure 24 illustrates aberrations of this example.

[0337] In Numerical Example 8, surfaces $r1 - r6$ belong to a positive first lens group $G1$, wherein $r3$ and $r4$ are aspherical surfaces (of a bi-aspherical surface lens). Surfaces $r7 - r14$ belong to a negative second lens group $G2$, wherein $r9$ and $r10$ are aspherical surfaces (of a bi-aspherical surface lens). Surfaces $r15 - r26$ belong to a positive third lens group $G3$, wherein $r20$ is an aspherical surface (of a mono-aspherical lens). Surfaces $r27 - r30$ belong to a negative fourth lens group $G4$, all of which are spherical surfaces. Surfaces $r31 - r48$ belong to a positive fifth lens group $G5$, wherein $r35$ and $r47$ are aspherical surfaces (of mono-aspherical surface lenses).

[0338] In this example, as shown in Table 8, first the condition of equation (1) for correction of the Petzval sum is satisfied. Then, as aspherical surfaces satisfying the conditions of equations (2) and (3), two aspherical surfaces (of a bi-aspherical surface lens) are placed in the first lens group, two aspherical surfaces (of a bi-aspherical surface lens) are placed in the second lens group, and one aspherical surface is placed in the third lens group. With this arrangement, the telecentricity, distortion aberration and curvature of field, for example, are corrected well.

[0339] The first lens group is provided by three positive lenses. The aspherical surfaces at $r3$ and $r4$ (of a bi-aspher-

ical surface lens) include regions in which their local curvature powers change with mutually opposite signs to cancel with each other, thus satisfying the functions defined by conditions (a1) and (a3) described above.

[0340] The second lens group is provided by four negative lenses. The aspherical surfaces r9 and r10 (of a bi-aspherical surface lens) include regions in which the local curvature powers change with mutually opposite signs to cancel with each other. Thus, the functions of conditions (a1) and (a2) are satisfied.

[0341] The third lens group is provided by five positive lenses and one negative lens. In the aspherical surface at r20, the local curvature power changes in the negative direction so as to correct the spherical aberration, for example.

[0342] The fourth lens group is provided by two negative lenses, and they function mainly to correct the Petzval sum.

[0343] The fifth lens group is provided by eight positive lenses and one negative lens. In the aspherical surface at r35, the local curvature power thereof changes in the negative direction, for correction of spherical aberration. The aspherical surface at r47 includes a region in which the local curvature power changes in the positive direction, for correction of distortion aberration, for example.

[0344] With this arrangement, aberrations are corrected satisfactorily, as illustrated in Figure 24.

[Example 9]

[0345] Figure 25 is a lens sectional view of a projection optical system according to Numerical Example 9 of the present invention. The projection optical system has a reference wavelength 193 nm, a numerical aperture $NA = 0.65$, a projection magnification $\beta = 1:4$, a lens conjugate distance $L = 1000$ mm, and an exposure region of diameter $\varnothing 27.3$ mm. This optical system is accomplished by lenses of a number 16 (sixteen) which is very small as a five-group type lens system. It uses seven aspherical surfaces, all of which are aspherical surfaces formed on lenses each having a plane surface at one side.

[0346] Table 9 shows specifications of this example, in regard to the conditions. Figure 26 illustrates changes in power of aspherical surfaces, wherein the axis of ordinate represents the height of aspherical surface from the optical axis, being standardized with respect to the effective diameter, and the axis of abscissa denotes the aspherical surface number. The leftward and rightward directions correspond to negative and positive directions of the change in local curvature power, respectively. Figure 27 illustrates aberrations of this example.

[0347] In Numerical Example 9, surfaces r1 - r4 belong to a positive first lens group G1, wherein r3 is an aspherical surface. Surfaces r5 - r10 belong to a negative second lens group G2, wherein r8 is an aspherical surface. Surfaces r11 - r16 belong to a positive third lens group G3, wherein r12 is an aspherical surface. Surfaces r17 - r20 belong to a negative fourth lens group G4, wherein r18 is an aspherical surface. Surfaces r21 - r32 belong to a positive fifth lens group G5, wherein r22, r25 and r31 are aspherical surfaces.

[0348] In this example, as shown in Table 9, first the condition of equation (1) for correction of the Petzval sum is satisfied. Then, as aspherical surfaces satisfying the conditions of equations (2) and (3), one aspherical surface is placed in the first lens group, and one aspherical surface is placed in the second lens group. With this arrangement, the telecentricity, distortion aberration and curvature of field, for example, are corrected well.

[0349] The first lens group is provided by two positive lenses. In the aspherical surface at r3, the local curvature power changes in the positive direction, thus satisfying the function defined by condition (a3) described above.

[0350] The second lens group is provided by three negative lenses. In the aspherical surface at r8, the local curvature power changes in the negative direction, thus satisfying the function of condition (a2). Simultaneously, the local curvature power changes in an opposite direction relative to that of the surface r3 of the first lens group, to cancel with each other. Thus, the function of condition (a1) described above is also satisfied.

[0351] The third lens group is provided by three positive lenses. In the aspherical surface at r12, the local curvature power changes in the negative direction so as to correct the spherical aberration, for example.

[0352] The fourth lens group is provided by two negative lenses. In the aspherical surface at r18, the local curvature power changes in the positive direction. This effectively cancel the diverging action which is produced by this lens group itself.

[0353] The fifth lens group is provided by six positive lenses. In the aspherical surfaces at r22, r25 and r31, the local curvature power thereof changes in the negative direction, for correction of spherical aberration. The aspherical surface at r31 also functions to correct distortion aberration.

[0354] In this example, each lens group is provided with an aspherical surface, such that aberrations are corrected satisfactorily, as illustrated in Figure 27.

[Example 10]

[0355] Figure 28 is a lens sectional view of a projection optical system according to Numerical Example 10 of the present invention. The projection optical system has a reference wavelength 193 nm, a numerical aperture $NA = 0.65$,

a projection magnification $\beta = 1:4$, a lens conjugate distance $L = 1000$ mm, and an exposure region of diameter $\varnothing 27.3$ mm. This optical system is accomplished by lenses of a number 16 (sixteen) which is very small as a five-group type lens system. It uses twelve aspherical surfaces, all of which are aspherical surfaces formed on bi-aspherical lenses each having two aspherical surfaces on both faces thereof.

[0356] Table 10 shows specifications of this example, in regard to the conditions. Figure 29 illustrates changes in power of aspherical surfaces, wherein the axis of ordinate represents the height of aspherical surface from the optical axis, being standardized with respect to the effective diameter, and the axis of abscissa denotes the aspherical surface number. The leftward and rightward directions correspond to negative and positive directions of the change in local curvature power, respectively. Figure 30 illustrates aberrations of this example.

[0357] In Numerical Example 10, surfaces r1 - r4 belong to a positive first lens group G1, wherein r3 and r4 are aspherical surfaces (of a bi-aspherical surface lens). Surfaces r5 - r10 belong to a negative second lens group G2, wherein r9 and r10 are aspherical surfaces (of a bi-aspherical surface lens). Surfaces r11 - r16 belong to a positive third lens group G3, wherein r13 and r14 are aspherical surfaces (of a bi-aspherical surface lens). Surfaces r17 - r20 belong to a negative fourth lens group G4, wherein r19 and r20 are aspherical surfaces (of a bi-aspherical surface lens). Surfaces r21 - r32 belong to a positive fifth lens group G5, wherein r21 and r22 as well as r25 and r26 are aspherical surfaces (of bi-aspherical surface lenses).

[0358] In this example, as shown in Table 10, first the condition of equation (1) for correction of the Petzval sum is satisfied. Then, as aspherical surfaces satisfying the conditions of equations (2) and (3), two aspherical surfaces (of a bi-aspherical surface lens) are placed in the first lens group, two aspherical surfaces (of a bi-aspherical surface lens) are placed in the second lens group, and two aspherical surfaces (of a bi-aspherical surface lens) are placed in the third lens group. With this arrangement, the telecentricity, distortion aberration and curvature of field, for example, are corrected well.

[0359] The first lens group is provided by two positive lenses. The aspherical surfaces at r3 and r4 include regions in which their local curvature powers change with mutually opposite signs to cancel with each other, thus satisfying the function defined by condition (a1) as well as the function of condition (a3) described above.

[0360] The second lens group is provided by three negative lenses. The aspherical surfaces at r9 and r10 (of a bi-aspherical surface lens) include regions in which their local curvature powers change with mutually opposite signs to cancel with each other, thus satisfying the function of condition (a1) as well as the function of condition (a2).

[0361] The third lens group is provided by three positive lenses. The aspherical surfaces at r13 and r14 include regions in which the local curvature powers change with mutually opposite signs to cancel with each other, thus satisfying the function as defined by condition (a1). In total, there remains the negative direction, for correction of spherical aberration, for example.

[0362] The fourth lens group is provided by two negative lenses. In the aspherical surfaces at r19 and r20 (of a bi-aspherical surface lens), the local curvature power changes in the positive direction. This effectively cancel the diverging action which is produced by this lens group itself.

[0363] The fifth lens group is provided by five positive lenses and one negative lens. The aspherical surfaces at r21 and r22 include regions in which the local curvature powers thereof change with mutually opposite signs. In total, there remains the negative direction, for correction of spherical aberration, for example.

[0364] In the aspherical surfaces at r25 and r26 (of a bi-aspherical surface lens), their local curvature powers change in the negative direction, and they functions mainly to correct spherical aberration. Also, four of the five positive lenses are made of fluorite ($n = 1.50140$), for correction of chromatic aberrations.

[0365] In this example, each lens group is provided with a bi-aspherical surface lens, such that aberrations are corrected satisfactorily, as illustrated in Figure 30.

[Example 11]

[0366] Figure 31 is a lens sectional view of a projection optical system according to Numerical Example 11 of the present invention. The projection optical system has a reference wavelength 248 nm, a numerical aperture $NA = 0.65$, a projection magnification $\beta = 1:5$, a lens conjugate distance $L = 1000$ mm, and an exposure region of diameter $\varnothing 31.3$ mm. This optical system is accomplished by lenses of a number 24 (twenty-four) which is relatively small as a five-group type lens system. It uses twelve aspherical surfaces, all of which are aspherical surfaces formed on bi-aspherical lenses each having two aspherical surfaces on both faces thereof.

[0367] Table 11 shows specifications of this example, in regard to the conditions. Figure 32 illustrates changes in power of aspherical surfaces, wherein the axis of ordinate represents the height of aspherical surface from the optical axis, being standardized with respect to the effective diameter, and the axis of abscissa denotes the aspherical surface number. The leftward and rightward directions correspond to negative and positive directions of the change in local curvature power, respectively. Figure 33 illustrates aberrations of this example.

[0368] In Numerical Example 11, surfaces r1 - r8 belong to a positive first lens group G1, all of which are spherical

surfaces. Surfaces r9 - r18 belong to a negative second lens group G2, wherein r12 and r13 are aspherical surfaces. Surfaces r19 - r28 belong to a positive third lens group G3, all of which are spherical surfaces. Surfaces r29 - r32 belong to a negative fourth lens group G4, wherein r29 and r32 are aspherical surfaces. Surfaces r33 - r48 belong to a positive fifth lens group G5, wherein r47 is an aspherical surface.

[0369] In this example, as shown in Table 11, first the condition of equation (1) for correction of the Petzval sum is satisfied. Then, as aspherical surfaces satisfying the conditions of equations (2) and (3), two aspherical surfaces are placed in the first lens group. With this arrangement, the telecentricity, distortion aberration and curvature of field, for example, are corrected well.

[0370] The first lens group is provided by three positive lenses and one negative lens, and telecentricity and distortion aberration, for example, are well corrected.

[0371] The second lens group is provided by one positive lens and four negative lenses. In the aspherical surface at r12, the local curvature power changes in the negative direction, thus satisfying the function of condition (a2). Simultaneously, the local curvature power changes in the opposite direction relative to that in the surface r13 to cancel with each other, and the function of condition (a1) is satisfied as well.

[0372] The third lens group is provided by five positive lenses.

[0373] The fourth lens group is provided by two negative lenses. In the aspherical surfaces at r29 and r32, their local curvature powers change with mutually opposite signs. In total, there remains the positive direction, and it effectively cancels the diverging action, at higher order, produced by this lens group itself.

[0374] The fifth lens group is provided by seven positive lenses and one negative lens. In the aspherical surface at r47, the local curvature power thereof changes in the negative direction, and the spherical aberration, coma aberration, and distortion, for example, are corrected thereby.

[0375] With this arrangement, aberrations are corrected satisfactorily, as illustrated in Figure 33.

[Example 12]

[0376] Figure 34 is a lens sectional view of a projection optical system according to Numerical Example 12 of the present invention. The projection optical system has a reference wavelength 193 nm, a numerical aperture NA = 0.65, a projection magnification $\beta = 1:4$, a lens conjugate distance $L = 1130$ mm, and an exposure region of diameter $\varnothing 27.3$ mm. This optical system is accomplished by lenses of a number 26 (twenty-six). It uses five aspherical surfaces.

[0377] Table 12 shows specifications of this example, in regard to the conditions. Figure 35 illustrates changes in power of aspherical surfaces, wherein the axis of ordinate represents the height of aspherical surface from the optical axis, being standardized with respect to the effective diameter, and the axis of abscissa denotes the aspherical surface number. The leftward and rightward directions correspond to negative and positive directions of the change in local curvature power, respectively. Figure 36 illustrates aberrations of this example.

[0378] In Numerical Example 12, surfaces r1 - r4 belong to a positive first lens group G1, wherein r3 is an aspherical surface. Surfaces r5 - r12 belong to a negative second lens group G2, wherein r8 and r9 are aspherical surfaces. Surfaces r13 - r18 belong to a positive third lens group G3, all of which are spherical surfaces. Surfaces r19 - r24 belong to a negative fourth lens group G4, all of which are spherical surfaces. Surfaces r25 - r34 belong to a positive fifth lens group G5, wherein r33 is an aspherical surface. Surfaces r35 - r40 belong to a negative sixth lens group G6, all of which are spherical surfaces. Surfaces r41 - r52 belong to a positive seventh lens group G7, wherein r52 is an aspherical surface.

[0379] In this example, as shown in Table 12, first the condition of equation (1) for correction of the Petzval sum is satisfied. Then, as aspherical surfaces satisfying the conditions of equations (2) and (3), one aspherical surface is placed in the first lens group, and two aspherical surfaces are placed in the second lens group. With this arrangement, the telecentricity, distortion aberration and curvature of field, for example, are corrected well.

[0380] The first lens group is provided by two positive lenses. In the aspherical surface at r3, the local curvature power changes in the negative direction.

[0381] The second lens group is provided by four negative lenses. In the aspherical surfaces at r8 and r9, the local curvature power changes in opposite directions, thus satisfying the function of condition (a1) and, simultaneously, the function of condition (a2). Also, through the relationship with the surfaces r3 and r8 of the first lens group, the function of condition (a1) is satisfied.

[0382] The third lens group is provided by three positive lenses.

[0383] The fourth lens group is provided by three negative lenses, and they serve mainly to correct the Petzval sum.

[0384] The fifth lens group is provided by five positive lenses. In the aspherical surface at r33, the local curvature power thereof at a peripheral portion changes slightly in the positive direction. This is effective to cancel, at higher orders, a strong diverging action of the subsequent sixth lens group.

[0385] The sixth lens group is provided by three negative lenses, and mainly they serve to correct the Petzval sum.

[0386] The seventh lens group is provided by six positive lenses. In the aspherical surface at r52, the local curva-

ture power changes in the negative direction, to thereby correct distortion and comma, for example.

[0387] With this arrangement, aberrations are corrected satisfactorily, as illustrated in Figure 36.

[Example 13]

[0388] Figure 37 is a lens sectional view of a projection optical system according to Numerical Example 13 of the present invention. The projection optical system has a reference wavelength 193 nm, a numerical aperture $NA = 0.65$, a projection magnification $\beta = 1:4$, a lens conjugate distance $L = 1130$ mm, and an exposure region of diameter $\varnothing 27.3$ mm. This optical system is accomplished by lenses of a number 26 (twenty-six). It uses three aspherical surfaces.

[0389] Table 13 shows specifications of this example, in regard to the conditions. Figure 38 illustrates changes in power of aspherical surfaces, wherein the axis of ordinate represents the height of aspherical surface from the optical axis, being standardized with respect to the effective diameter, and the axis of abscissa denotes the aspherical surface number. The leftward and rightward directions correspond to negative and positive directions of the change in local curvature power, respectively. Figure 39 illustrates aberrations of this example.

[0390] In Numerical Example 13, surfaces r1 - r6 belong to a positive first lens group G1, all of which are spherical surfaces. Surfaces r7 - r12 belong to a negative second lens group G2, all of which are spherical surfaces. Surfaces r13 - r18 belong to a positive third lens group G3, all of which are spherical surfaces. Surfaces r19 - r24 belong to a negative fourth lens group G4, wherein r19 and r20 are aspherical surfaces. Surfaces r25 - r34 belong to a positive fifth lens group G5, all of which are spherical surface. Surfaces r35 - r40 belong to a negative sixth lens group G6, all of which are spherical surfaces. Surfaces r41 - r52 belong to a positive seventh lens group G7, wherein r49 is an aspherical surface.

[0391] In this example, as shown in Table 13, first the condition of equation (1) for correction of the Petzval sum is satisfied. Then, as aspherical surfaces satisfying the conditions of equations (2) and (3), two aspherical surfaces are placed in the fourth lens group, by which the telecentricity, distortion aberration and curvature of field, for example, are corrected well.

[0392] The first lens group is provided by three positive lenses.

[0393] The second lens group is provided by three negative lenses.

[0394] The third lens group is provided by three positive lenses.

[0395] The fourth lens group is provided by three negative lenses, and they serve mainly to correct the Petzval sum.

In the surfaces r19 and r21, the local curvature powers slightly change in opposite directions, thus satisfying the function as defined by condition (a1) described above. In total, there remains the positive direction, which is effective to cancel, at higher orders, the diverging action of this lens group.

[0396] The fifth lens group is provided by five positive lenses.

[0397] The sixth lens group is provided by three negative lenses, and mainly they serve to correct the Petzval sum.

[0398] The seventh lens group is provided by six positive lenses. In the aspherical surface at r49, the local curvature power changes in the negative direction, to thereby correct distortion and comma, for example.

[0399] With this arrangement, aberrations are corrected satisfactorily, as illustrated in Figure 39.

[Example 14]

[0400] Figure 40 is a lens sectional view of a projection optical system according to Numerical Example 14 of the present invention. The projection optical system has a reference wavelength 193 nm, a numerical aperture $NA = 0.65$, a projection magnification $\beta = 1:4$, a lens conjugate distance $L = 1000$ mm, and an exposure region of diameter $\varnothing 27.3$ mm. This optical system is accomplished by lenses of a number 22 (twenty-two) which is small as a seven-group type lens system. It uses four aspherical surfaces.

[0401] Table 14 shows specifications of this example, in regard to the conditions. Figure 41 illustrates changes in power of aspherical surfaces, wherein the axis of ordinate represents the height of aspherical surface from the optical axis, being standardized with respect to the effective diameter, and the axis of abscissa denotes the aspherical surface number. The leftward and rightward directions correspond to negative and positive directions of the change in local curvature power, respectively. Figure 42 illustrates aberrations of this example.

[0402] In Numerical Example 14, surfaces r1 - r4 belong to a positive first lens group G1, wherein r3 is an aspherical surface. Surfaces r5 - r10 belong to a negative second lens group G2, wherein r8 is an aspherical surfaces. Surfaces r11 - r16 belong to a positive third lens group G3, wherein r13 is an aspherical surface. Surfaces r17 - r20 belong to a negative fourth lens group G4, all of which are spherical surfaces. Surfaces r21 - r26 belong to a positive fifth lens group G5, all of which are spherical surfaces. Surfaces r27 - r30 belong to a negative sixth lens group G6, all of which are spherical surfaces. Surfaces r31 - r44 belong to a positive seventh lens group G7, wherein r43 is an aspherical surface.

[0403] In this example, as shown in Table 14, first the condition of equation (1) for correction of the Petzval sum is

satisfied. Then, as aspherical surfaces satisfying the conditions of equations (2) and (3), one aspherical surface is placed in the first lens group, one aspherical surface is placed in the second lens group, and one aspherical surface is placed in the third lens group. With this arrangement, the telecentricity, distortion aberration, curvature of field, and sagittal transverse aberration, for example, are well corrected.

5 [0404] The first lens group is provided by two positive lenses. In the aspherical surface at r3, the local curvature power changes in the negative direction, this being effective to cancel, at higher orders, the converging action of this lens group itself.

[0405] The second lens group is provided by three negative lenses. In the aspherical surface at r8, the local curvature power changes, in the central portion, in negative direction and thus the function of condition (a1) is satisfied. In the peripheral portion, the power changes in the positive direction to thereby cancel, at higher orders, the diverging action of this lens group itself. Further, in the peripheral portion, the change in the local curvature power is in the opposite direction in relation to the surface r3 of the first lens group, such that the function defined by condition (a1) is satisfied.

10 [0406] The third lens group is provided by three positive lenses. In the aspherical surface at r13, the local curvature power changes, in the central portion, in the positive direction and thus the function of condition (a1) is satisfied. In the peripheral portion, the power changes in the negative direction to thereby cancel, at higher orders, the converging action of this lens group itself. Further, in the peripheral portion, the change in the local curvature power is in the opposite direction in relation to the surface r8 of the second lens group, such that the function defined by condition (a1) is satisfied.

20 [0407] The fourth lens group is provided by two negative lenses, and they serve mainly to correct the Petzval sum.

[0408] The fifth lens group is provided by three positive lenses.

[0409] The sixth lens group is provided by two negative lenses, and mainly they serve to correct the Petzval sum.

[0410] The seventh lens group is provided by six positive lenses and one negative lens. The aspherical surface at r43 includes a region in which the local curvature power changes in the negative direction, to thereby correct spherical aberration, comma, and distortion, for example.

25 [0411] With this arrangement, aberrations are corrected satisfactorily, as illustrated in Figure 42.

[Example 15]

30 [0412] Figure 43 is a lens sectional view of a projection optical system according to Numerical Example 15 of the present invention. The projection optical system has a reference wavelength 193 nm, a numerical aperture $NA = 0.65$, a projection magnification $\beta = 1:4$, a lens conjugate distance $L = 1000$ mm, and an exposure region of diameter $\varnothing 27.3$ mm. This optical system is accomplished by lenses of a number 20 (twenty) which is small as a seven-group type lens system. It uses eight aspherical surfaces.

35 [0413] Table 15 shows specifications of this example, in regard to the conditions. Figure 44 illustrates changes in power of aspherical surfaces, wherein the axis of ordinate represents the height of aspherical surface from the optical axis, being standardized with respect to the effective diameter, and the axis of abscissa denotes the aspherical surface number. The leftward and rightward directions correspond to negative and positive directions of the change in local curvature power, respectively. Figure 45 illustrates aberrations of this example.

40 [0414] In Numerical Example 15, surfaces r1 - r4 belong to a positive first lens group G1, wherein r2 is an aspherical surface. Surfaces r5 - r8 belong to a negative second lens group G2, wherein r8 is an aspherical surface. Surfaces r9 - r12 belong to a positive third lens group G3, wherein r10 is an aspherical surface. Surfaces r13 - r16 belong to a negative fourth lens group G4, wherein r15 is an aspherical surface. Surfaces r17 - r22 belong to a positive fifth lens group G5, wherein r18 is an aspherical surface. Surfaces r23 - r26 belong to a negative sixth lens group G6, wherein r25 is an aspherical surface. Surfaces r27 - r40 belong to a positive seventh lens group G7, wherein r30 and r39 are aspherical surfaces.

[0415] In this example, as shown in Table 15, first the condition of equation (1) for correction of the Petzval sum is satisfied. Then, as aspherical surfaces satisfying the conditions of equations (2) and (3), one aspherical surface is introduced into each of the first, second, third, and fourth lens groups, by which the telecentricity, distortion aberration, curvature of field, and sagittal transverse aberration, for example, are well corrected.

50 [0416] The first lens group is provided by two positive lenses. In the aspherical surface at r2, the local curvature power changes in the positive direction, thus satisfying the function of condition (a3) described above.

[0417] The second lens group is provided by two negative lenses. In the aspherical surface at r8, the local curvature power changes in the negative direction, thus satisfying the function of condition (a2). Further, the change in the local curvature power is in the opposite direction in relation to the surface r2 of the first lens group, such that also the function defined by condition (a1) is satisfied.

55 [0418] The third lens group is provided by two positive lenses. In the aspherical surface at r10, the local curvature power changes in the positive direction, thus satisfying the function of condition (a3). Further, the change in the local

curvature power is in the opposite direction in relation to the surface r8 of the second lens group, such that also the function defined by condition (a1) is satisfied.

[0419] The fourth lens group is provided by two negative lenses, and they serve mainly to correct the Petzval sum. In the aspherical surface at r15, the local curvature power changes in the negative direction, in the central portion thereof, thus satisfying the function as defined by condition (a2) described above. In the peripheral portion, it changes in the positive direction, which is effective to cancel, at higher orders, the diverging action of this lens group itself.

[0420] The fifth lens group is provided by three positive lenses. The aspherical surface at r18 includes a region in which the local curvature power changes in the negative direction, thus correcting the spherical aberration, for example.

[0421] The sixth lens group is provided by two negative lenses, and mainly they serve to correct the Petzval sum. In the aspherical surface at r25, the local curvature power changes in the negative direction, in the central portion, whereas it changes in the positive direction, in the peripheral portion. This effectively cancel, at higher orders, the diverging action of this lens group itself.

[0422] The seventh lens group is provided by six positive lenses and one negative lens. The aspherical surface at r30 include a region in which the local curvature power changes in the negative direction, to thereby mainly correct spherical aberration. In the aspherical surface 39r, the change in local curvature power at the central portion is slightly in the negative direction, while at the peripheral portion it is in the positive direction, by which distortion and comma are corrected.

[0423] With this arrangement, aberrations are corrected satisfactorily, as illustrated in Figure 45.

[Example 16]

[0424] Figure 46 is a lens sectional view of a projection optical system according to Numerical Example 16 of the present invention. The projection optical system has a reference wavelength 193 nm, a numerical aperture NA = 0.65, a projection magnification $\beta = 1:4$, a lens conjugate distance $L = 1000$ mm, and an exposure region of diameter $\varnothing 27.3$ mm. This optical system is accomplished by lenses of a number 17 (seventeen) which is extraordinarily small as a seven-group type lens system. It uses eight aspherical surfaces, all being provided on bi-aspherical surface lens.

[0425] Table 16 shows specifications of this example, in regard to the conditions. Figure 47 illustrates changes in power of aspherical surfaces, wherein the axis of ordinate represents the height of aspherical surface from the optical axis, being standardized with respect to the effective diameter, and the axis of abscissa denotes the aspherical surface number. The leftward and rightward directions correspond to negative and positive directions of the change in local curvature power, respectively. Figure 48 illustrates aberrations of this example.

[0426] In Numerical Example 16, surfaces r1 - r2 belong to a positive first lens group G1, wherein r1 and r2 are aspherical surfaces (of a bi-aspherical surface lens). Surfaces r3 - r4 belong to a negative second lens group G2, wherein r3 and r4 are aspherical surfaces (of a bi-aspherical surface lens). Surfaces r5 - r8 belong to a positive third lens group G3, all of which are spherical surfaces. Surfaces r9 - r12 belong to a negative fourth lens group G4, wherein r9 and r10 are aspherical surfaces (of a bi-aspherical surface lens). Surfaces r13 - r16 belong to a positive fifth lens group G5, all of which are spherical surfaces. Surfaces r17 - r20 belong to a negative sixth lens group G6, all of which are spherical surfaces. Surfaces r21 - r34 belong to a positive seventh lens group G7, wherein r33 and r34 are aspherical surfaces (of a bi-aspherical surface lens).

[0427] In this example, as shown in Table 16, first the condition of equation (1) for correction of the Petzval sum is satisfied. Then, as aspherical surfaces satisfying the conditions of equations (2) and (3), one aspherical surface is introduced into each of the first, second, fourth and seventh lens groups, by which the telecentricity, distortion aberration, and curvature of field, for example, are well corrected.

[0428] The first lens group is provided by one positive lens. The aspherical surface at r1 and r2 include regions in which their local curvature powers change with mutually opposite signs, thus satisfying the function of condition (a1) described above as well as the function of condition (a3). In total, there remains the power change in the positive direction.

[0429] The second lens group is provided by one negative lens. The aspherical surfaces at r3 and r4 includes regions in which the local curvature powers change with mutually opposite signs, thus satisfying the functions of conditions (a1) and (a2). In total, there remains a power change in the negative direction, and the group is in the cancelling relation with the first group. Also in this respect, the function defined by condition (a1) is satisfied.

[0430] The third lens group is provided by two positive lenses, and they are effective to correct meridional or sagittal transverse aberrations.

[0431] The fourth lens group is provided by two negative lenses. The aspherical surfaces at r9 and r10 are in a weak cancelling relation with each other, at the outermost peripheral portion. In total, however, a power change in the positive direction remains. Thus, it functions to cancel the diverging action of this lens system itself.

[0432] The fifth lens group is provided by two positive lenses.

[0433] The sixth lens group is provided by two negative lenses, and mainly they serve to correct the Petzval sum.

[0434] The seventh lens group is provided by six positive lenses and one negative lens. In the aspherical surfaces at r33 and r34, their local curvature powers change with mutually opposite signs, in the peripheral portion, thus satisfying the function of condition (a1) described above. In total, a power change in the negative direction remains, which effectively correct distortion, comma and spherical aberration, for example.

[0435] With this arrangement, aberrations are corrected satisfactorily, as illustrated in Figure 48.

[Example 17]

[0436] Figure 49 is a lens sectional view of a projection optical system according to Numerical Example 17 of the present invention, which is particularly suitably used in an apparatus for producing a pattern for a liquid crystal device. The projection optical system has a reference wavelength 435.8 nm (g-line), a numerical aperture $NA = 0.10$, a projection magnification $\beta = 1:1.25$, a lens conjugate distance $L = 1250$ mm, and an exposure region of diameter $\varnothing 85.0$ mm. This optical system is accomplished by lenses of a small number 26 (twenty). It uses five aspherical surfaces.

[0437] Table 17 shows specifications of this example, in regard to the conditions. Figure 50 illustrates changes in power of aspherical surfaces, wherein the axis of ordinate represents the height of aspherical surface from the optical axis, being standardized with respect to the effective diameter, and the axis of abscissa denotes the aspherical surface number. The leftward and rightward directions correspond to negative and positive directions of the change in local curvature power, respectively. Figure 51 illustrates aberrations of this example.

[0438] Chromatic aberration is taken into consideration in this example. When glass materials have following refractive indices (n) with respect to g-line:

Refractive Index n = 1.603377
= 1.594224
= 1.480884

then, they have following refractive indices with respect to h-line (404.7 nm):

Refractive index n = 1.607780
= 1.600939
= 1.483290

[0439] In Numerical Example 17, surfaces r1 - r8 belong to a positive first lens group G1, wherein r2 is an aspherical surface. Surfaces r9 - r16 belong to a negative second lens group G2, wherein r13 is an aspherical surface. Surfaces r17 - r18 belong to a positive third lens group G3, all of which are spherical surfaces. Surfaces r19 - r24 belong to a negative fourth lens group G4, all of which are spherical surfaces. Surfaces r25 - r30 belong to a positive fifth lens group G5, wherein r27 is an aspherical surface. Surfaces r31 - r42 belong to a negative sixth lens group G6, wherein r34 is an aspherical surface. Surfaces r43 - r48 belong to a positive seventh lens group G7, wherein r47 is an aspherical surface.

[0440] In this example, as shown in Table 17, first the condition of equation (1) for correction of the Petzval sum is satisfied. Then, as aspherical surfaces satisfying the conditions of equations (2) and (3), one aspherical surface is introduced into each of the first, second, sixth and seventh lens groups, by which the telecentricity, distortion aberration, and curvature of field, for example, are well corrected. This optical system has a magnification 1.25x which is greater than the unit magnification, and, even at the image plane side, a chief ray passes a high position. Therefore, introducing an aspherical surface also into the sixth and seventh lens group is effective.

[0441] In the aspherical surface r13 of the second lens group, the function of condition (a2) described above is satisfied. Also, through the relation with the aspherical surface r34 of the sixth lens group and the aspherical surface r47 of the seventh lens group, the function defined by condition (a1) is satisfied.

[0442] In the aspherical surface r27 of the fifth lens group, the local curvature power changes in the negative direction and, thus, mainly the spherical aberration is corrected.

[0443] With this arrangement, aberrations are corrected satisfactorily, as illustrated in Figure 51.

[Example 18]

[0444] Figure 55 is a lens sectional view of a projection optical system according to Numerical Example 18 of the present invention. The projection optical system has a reference wavelength 193 nm, a numerical aperture $NA = 0.65$, a projection magnification $\beta = 1:4$, a lens conjugate distance $L = 1000$ mm, and an exposure region of diameter $\varnothing 27.3$ mm. This optical system is accomplished by lenses of a small number 13 (thirteen). It uses five aspherical surfaces.

[0445] Table 18 shows specifications of this example, in regard to the conditions. Figure 56 illustrates changes in

power of aspherical surfaces, wherein the axis of ordinate represents the height of aspherical surface from the optical axis, being standardized with respect to the effective diameter, and the axis of abscissa denotes the aspherical surface number. The leftward and rightward directions correspond to negative and positive directions of the change in local curvature power, respectively. Figure 57 illustrates aberrations of this example.

[0446] In Numerical Example 18, surfaces r1 - r8 belong to a positive first lens group G1, wherein r2 and r5 are aspherical surfaces. Surfaces r9 - r14 belong to a negative second lens group G2, wherein r10 and r12 are aspherical surfaces. Surfaces r15 - r26 belong to a positive third lens group G3, wherein r19 is an aspherical surface.

[0447] In this example, as shown in Table 18, first the condition of equation (1) for correction of the Petzval sum is satisfied. Then, as aspherical surfaces satisfying the conditions of equations (2) and (3), four aspherical surface are used. Namely, two aspherical surfaces are placed in the first lens group, and two aspherical surfaces are placed in the second lens group. With this arrangement, the telecentricity, distortion aberration and curvature of field, for example, are corrected well.

[0448] The first lens group is provided by one negative lens and three positive lenses. In the aspherical surfaces at r2 and r5, their local curvature powers gradually change in the positive direction. Thus, the function as defined by condition (b2) described above is satisfied.

[0449] The second lens group is provided by three negative lenses. The aspherical surfaces at r10 and r12 include regions in which their local curvature powers change with mutually opposite signs to cancel with each other, for correction for correction of higher orders of field curvature and distortion, for example. Thus, the function as defined by condition (b1) described above is satisfied.

[0450] Additionally, in the relationship between the surface r10 and the surfaces r2 and r5 of the first lens group, there are regions in which the local curvature powers change with mutually opposite signs. Thus, also in this respect, the function of condition (b1) is satisfied. This is effective for correction of the telecentricity and distortion, for example.

[0451] The third lens group is provided by five positive lenses and one negative lens. Only the surface at r19 is an aspherical surface wherein the local curvature power changes in the negative direction mainly for correction of the spherical aberration. Thus, the functions of conditions (b3) and (b4) described above are satisfied.

[0452] In the lens system, a pair of lenses, comprising a negative meniscus lens having its concave surface facing to the image plane side and a positive meniscus lens having a first concave surface facing to the image plane side, are disposed, to assist correction of field curvature, comma aberration and distortion aberration.

[0453] With this arrangement, aberrations are corrected satisfactorily, as illustrated in Figure 57.

[Example 19]

[0454] Figure 58 is a lens sectional view of a projection optical system according to Numerical Example 19 of the present invention. The projection optical system has a reference wavelength 193 nm, a numerical aperture $NA = 0.65$, a projection magnification $\beta = 1:4$, a lens conjugate distance $L = 1000$ mm, and an exposure region of diameter $\varnothing 27.3$ mm. This optical system is accomplished by lenses of a small number 14 (fourteen). It uses eight aspherical surfaces.

[0455] Table 19 shows specifications of this example, in regard to the conditions. Figure 59 illustrates changes in power of aspherical surfaces, wherein the axis of ordinate represents the height of aspherical surface from the optical axis, being standardized with respect to the effective diameter, and the axis of abscissa denotes the aspherical surface number. The leftward and rightward directions correspond to negative and positive directions of the change in local curvature power, respectively. Figure 60 illustrates aberrations of this example.

[0456] In Numerical Example 19, surfaces r1 - r6 belong to a positive first lens group G1, wherein r1 and r2 are aspherical surfaces. Surfaces r7 - r12 belong to a negative second lens group G2, wherein r8, r9 and r10 are aspherical surfaces. Surfaces r13 - r28 belong to a positive third lens group G3, wherein r16, r21 and r27 are aspherical surfaces.

[0457] Each of the lenses having surfaces r1 and r2; r8 and r9 is a bi-aspherical surface lens having aspherical surfaces on both sides thereof.

[0458] In this example, as shown in Table 19, first the condition of equation (1) for correction of the Petzval sum is satisfied. Then, as aspherical surfaces satisfying the conditions of equations (2) and (3), five aspherical surface are used. Namely, two aspherical surfaces are placed in the first lens group, and three aspherical surface is placed in the second lens group. With this arrangement, the telecentricity, distortion aberration and curvature of field, for example, are corrected well.

[0459] The first lens group is provided by three positive lenses. In the aspherical surfaces at r1 and r2 which are the surfaces of a bi-aspherical surface lens, their local curvature powers change with mutually opposite signs to cancel with each other, thus satisfying the function defined by condition (b1) described above and, simultaneously, the function of condition (b2) described above.

[0460] The second lens group is provided by three negative lenses. At the aspherical surfaces r9 and r10 which are the surfaces of a bi-aspherical surface lens, the local curvature powers change with mutually opposite signs to cancel with each other. Thus, the function of condition (b1) is satisfied.

[0461] Similarly, between the surfaces r8 and r10, between the surfaces r2 and r8, and between the surfaces r2 and r9, the function defined by condition (b1) is satisfied. Thus, through mutual cancellation, the telecentricity, distortion and field curvature, for example, are well corrected. Further, because a bi-aspherical surface lens is used to provide the function of condition (b1), the influence of any eccentricity due to the lens manufacture can be reduced.

[0462] The third lens group is provided by seven positive lenses and one negative lens. In the aspherical surfaces at r16 and r21, the local curvature power changes in the negative direction so as mainly to correct the spherical aberration. Thus, the function of condition (b3) is satisfied. In the aspherical surface at r27, the local curvature power thereof at the peripheral portion changes in the positive direction, thus satisfying the function of condition (b4).

[0463] In the lens system, a pair of lenses, comprising a negative lens having a second concave surface facing to the image plane side and a positive meniscus lens having its first concave surface facing to the image plane side, are disposed, to assist correction of field curvature, comma aberration and distortion aberration.

[0464] With this arrangement, aberrations are corrected satisfactorily, as illustrated in Figure 60.

[Examples 20 - 24]

[0465] Next, important features of lens structures of projection optical systems according to Numerical Examples 20 - 24 of the present invention will be described. In these examples, the projection optical system is made substantially telecentric on the object side (reticle side) and on the image plane side (wafer side). It has a projection magnification $\beta = 1:4$, a numerical aperture $NA = 0.65$, and an object-to-image distance (from object plane to image plane) $L = 1000$ mm. The reference wavelength is 193 nm. As regards the picture plane range, the diameter of an exposure area on a wafer is $\varnothing 27.3$ mm.

[0466] In Figures 62, 65, 68, 71 and 74, the axis of ordinate represents the height of aspherical surface from the optical axis, being standardized with respect to the effective diameter, and the axis of abscissa denotes the aspherical surface number. The leftward and rightward directions correspond to negative and positive directions of the change in local curvature power, respectively.

(Example 20)

[0467] In Numerical Example 20 shown in Figure 61, the lens system comprises, in an order from the object side, a first lens group L1 having a positive refractive power, a second lens group L2 having a negative refractive power, a third lens group L3 having a positive refractive power, a fourth lens group L4 having a negative refractive power, and a fifth lens group L5 having a positive refractive power and including a front unit L51 with a positive refractive power and a rear unit L52 having a positive refractive power.

[0468] The lens optical system uses seven aspherical surfaces. Table 20 shows values corresponding to conditions of equations (2), (3) and (1). In Table 20, only those aspherical surfaces that satisfy condition (2) are shown. Figure 63 shows aberrations, and Figure 62 shows changes in local curvature power of the aspherical surface.

[0469] Details of the lens structure will be described below.

[0470] The first lens group L1 comprises, in an order from the object side, a positive lens of plane-convex shape having a convex surface facing to the image plane side, a positive lens of meniscus shape having a concave surface facing to the object side, an aspherical surface lens of meniscus shape having a convex surface facing to the object side.

[0471] The aspherical surface at r5 includes a region in which the local curvature power changes in the positive direction, satisfying the function of (c3) described above. With this aspherical surface, mainly a positive distortion is produced to contribute correction of distortion aberration.

[0472] The second lens group L2 comprises, in an order from the object side, a negative lens of meniscus shape having a concave surface facing to the image side, an aspherical surface negative lens of biconcave shape, and a negative lens of biconcave shape.

[0473] With the placement of plural negative lenses as in this example, the Petzval sum is well corrected while dispersing a strong refractive power. The aspherical surface at r10 includes a region in which the local curvature power changes in the negative direction, satisfying the function of condition (c2) described above. Also, in the relation with the surface r10 of the first lens group L1, there are regions in which the local curvature powers change in the opposite directions, thus satisfying the function of condition (c1).

[0474] The third lens group L3 has a positive refractive power so as to transform a divergent light from the second lens group L2 into a convergent light. In an order from the object side, it comprises a positive lens of biconvex shape, an aspherical surface positive lens of biconvex shape, and a positive lens of biconvex shape. Due to the strong positive refractive power of the third lens group L3, the incidence height on the fourth lens group L4 having a negative refractive power is made low and, by making the refractive power of the fourth lens group L4 strong, the Petzval sum is corrected satisfactorily. Further, with use of an aspherical surface, spherical aberration and comma aberration are well corrected.

[0475] The fourth lens group L4 comprises, in an order from the object side, a negative lens of biconcave shape, and an aspherical surface negative lens of biconcave shape. The fourth lens group L4 and the second lens group L2 bear a strong negative refractive power, by which the Petzval sum can be corrected successfully. Further, by use of an aspherical surface, mainly spherical aberration and coma aberration which are produced at a concave surface having a strong curvature can be corrected effectively.

[0476] The fifth lens group L5 has a positive refractive power, so that an optical system being telecentric on the image side is provided. In an order from the object side, it comprises an aspherical surface positive lens of biconvex shape, a positive lens of biconvex shape, an aspherical surface positive lens of biconvex shape, a positive lens of meniscus shape having a concave surface facing to the image side, a positive lens of meniscus shape having a concave surface facing to the image side, and an aspherical surface negative lens of meniscus shape having a concave surface facing to the image side.

[0477] The aspherical surface used at a concave surface close to the image plane is contributable mainly to correction of coma and distortion.

[0478] In this example, by using seven aspherical surface lenses, an optical system of large numerical aperture (NA) is provided with a lens number of 17 (seventeen).

[0479] In this example, each of the first to fourth lens groups L1 - L4 is provided with one aspherical surface while the fifth lens group L5 is provided with three aspherical surfaces. However, each of the first to fourth lens groups may have more than one aspherical surface. Also, there may be a lens group having no aspherical surface. This is also with the case of other examples to be described below.

(Example 21)

[0480] Figure 64 shows Numerical Example 21 which differs from Numerical Example 20 of Figure 61 in the point of the lens structure of the first and fifth lens groups L1 and L5 and the magnification and focal length of each lens group. The remaining portion has essentially the same structure.

[0481] The lens optical system uses eight aspherical surfaces. Table 21 shows values corresponding to conditions of equations (2), (3) and (1). Figure 66 shows aberrations, and Figure 65 shows changes in local curvature power of the aspherical surface.

[0482] Details of the lens structure will be described below.

[0483] The first lens group L1 comprises, in an order from the object side, an aspherical surface positive lens of biconvex shape, a negative lens of meniscus shape having a concave surface facing to the image side, and a positive lens of biconvex shape. The aspherical surface on the second surface is effective to correct, with good balance, the distortion aberration produced at the first and second lens groups L1 and L2.

[0484] The second lens group L2 comprises, in an order from the object side, two negative lenses of approximately plane-concave shape having a concave surface facing to the image side, and an aspherical surface negative lens of biconcave shape.

[0485] The aspherical surface at r10 includes a region in which the local curvature power changes in the negative direction, thus satisfying the function of condition (c2) described above. Also, in the relation between the surfaces r10 and r11, there are regions in which the local curvature powers change in the opposite directions, thus satisfying the function of condition (c1). Further, the surface r2 of the first lens group L1 and the surface r11 of the second lens group L2 include regions in which their local curvature powers change in opposite directions, and the function of condition (c1) described above is satisfied.

[0486] The third lens group L3 comprises, in an order from the object side, a positive lens of meniscus shape having a convex surface facing to the image side, a positive lens of biconvex shape, and an aspherical surface positive lens of biconvex shape.

[0487] In this example, a fluorite lens is introduced into the third lens group L3, and a similar fluorite lens is used in the fifth lens group L5, for correction of chromatic aberration.

[0488] The fourth lens group L4 comprises, in an order from the object side, a negative lens of biconcave shape, and an aspherical surface negative lens of biconcave shape. By use of an aspherical surface, spherical aberration and coma aberration, for example, which are produced at a concave surface having a strong curvature can be corrected effectively.

[0489] The fifth lens group L5 comprises, in order from the object side, an aspherical surface positive lens of meniscus shape having a convex surface facing to the image side, a positive lens of biconvex shape, an aspherical surface positive lens of biconvex shape, two positive lenses of meniscus shape having a concave surface facing to the image side, a negative lens of meniscus shape having a concave surface facing to the image side, and an aspherical surface positive lens of meniscus shape having a concave surface facing to the image side.

[0490] In the fifth lens group L5, an aspherical surface is placed at a position where an axial light flux, which is a light flux emitted from an optical axis upon the object plane, is high, and this aspherical surface is used mainly for cor-

rection of negative spherical aberration to be produced in the fifth lens group L5 having a strong positive refractive power.

[0491] The aspherical surface used at a convex surface adjacent to the image plane is mainly contributable to correction of coma and distortion.

5 **[0492]** In this example, by using eight aspherical surface lenses, an optical system of large numerical aperture (NA) is provided with a lens number of 19 (nineteen).

(Example 22)

10 **[0493]** Figure 67 Shows Numerical Example 22 in which the lens optical system uses seven aspherical surfaces. Table 22 shows values corresponding to conditions of equations (2), (3) and (1). Figure 69 shows aberrations, and Figure 68 shows changes in local curvature power of the aspherical surface. A main difference of this example over Numerical Example 20 is that the aspherical surface lenses include at least one aspherical surface lens having a plane surface at a side opposite to the aspherical surface thereof. In this example, six of seven aspherical surface lenses has a plane surface formed at a side opposite to an aspherical surface thereof.

15 **[0494]** Details of the lens structure will be described below.

[0495] The first lens group L1 comprises, in an order from the object side, a positive lens of plane-convex shape having a convex surface facing to the image side, and an aspherical surface positive lens of plane-convex shape having a convex surface facing to the object side. The aspherical surface at r3 includes a region in which the local curvature power changes in the positive direction, thus satisfying the function defined by condition (c3) described above.

20 **[0496]** The second lens group L2 comprises, in an order from the object side, a negative lens of meniscus shape having a concave surface facing to the image side, an aspherical surface negative lens of plane-concave shape, and a negative lens of biconcave shape. With a strong negative refractive power, the Petzval sum is corrected satisfactorily. The aspherical surface at r8 includes a region in which the local curvature power changes in the negative direction, thus satisfying the function defined by condition (c2) described above. Also, in the relation with the surface r3 of the first lens group L1, there are regions in which their local curvature powers change in mutually opposite directions. Thus, also the function defined by condition (c1) described above is satisfied.

25 **[0497]** The third lens group L3 comprises, in an order from the object side, an aspherical surface positive lens having a convex surface facing to the image side, and two positive lenses of biconvex shape. Since the third lens group L3 should have a strong positive refractive power, it is provided by plural positive lenses.

30 **[0498]** The fourth lens group L4 comprises, in an order from the object side, an aspherical surface negative lens of plane-concave shape having a concave surface facing to the image plane, and a negative lens of biconcave shape. By use of an aspherical surface, higher order spherical aberration and coma aberration, for example, which are produced at a concave surface having a strong curvature can be corrected effectively.

35 **[0499]** The fifth lens group L5 comprises, in order from the object side, an aspherical surface positive lens of plane-convex shape having a convex surface facing to the image side, a positive lens of biconvex shape, an aspherical surface positive lens of plane-convex shape having a convex surface facing to the object side, a positive lens of meniscus shape having a concave surface facing to the image side, a negative lens of meniscus shape having a concave surface facing to the image side, and an aspherical surface positive lens of meniscus shape having a concave surface facing to the image side.

40 **[0500]** In the fifth lens group L5, the aspherical surface is placed at a position where an axial light flux, which is a light flux emitted from an optical axis upon the object plane, is high, and this aspherical surface is used mainly for correction of negative spherical aberration to be produced in the fifth lens group L5 having a strong positive refractive power.

45 **[0501]** In this example, by using seven aspherical surface lenses, an optical system of large numerical aperture (NA) is provided with a lens number of 16 (sixteen).

(Example 23)

50 **[0502]** Figure 70 shows Numerical Example 23 which differs from Numerical Example 22 of Figure 67 mainly in the point of the lens structures of second, third and fifth lens groups L2, L3 and L5.

[0503] In this example, six of seven aspherical surface lenses has a plane surface formed at a side opposite to an aspherical surface thereof.

55 **[0504]** The lens optical system uses seven aspherical surfaces. Table 23 shows values corresponding to conditions of equations (2), (3) and (1). Figure 72 shows aberrations, and Figure 71 shows changes in local curvature power of the aspherical surface.

[0505] Details of the lens structure will be described below.

[0506] The first lens group L1 comprises, in an order from the object side, an aspherical surface positive lens of

plane-convex shape having a convex surface facing to the image side, and an aspherical surface positive lens of plane-convex shape having a convex surface facing to the object side. The aspherical surface at r3 includes a region in which the local curvature power changes in the positive direction, thus satisfying the function defined by condition (c3) described above.

[0507] The second lens group L2 comprises, in an order from the object side, an aspherical surface negative lens of plane-concave shape having a concave surface facing to the image side, and a negative lens of biconcave shape. The aspherical surface at r8 includes a region in which the local curvature power changes in the negative direction, thus satisfying the function defined by condition (c2) described above. Also, in the relation with the surface r3 of the first lens group L1, there are regions in which their local curvature powers change in mutually opposite directions. Thus, also the function defined by condition (c1) described above is satisfied. Further, in the relation with the surface r6 of the second lens group L2, it is seen that there are regions in which their local curvature powers change in mutually opposite directions.

[0508] The third lens group L3 comprises, in an order from the object side, an aspherical surface positive lens of plane-convex shape having a convex surface facing to the image side, two positive lenses of biconvex shape, and a positive meniscus lens having a concave surface facing to the image side.

[0509] The fourth lens group L4 comprises, in an order from the object side, an aspherical surface negative lens of plane-concave shape having a concave surface facing to the image side, and a negative lens of biconcave shape.

[0510] The fifth lens group L5 comprises, in order from the object side, an aspherical surface positive lens of plane-convex shape having a convex surface facing to the image plane side, a positive lens of biconvex shape, an aspherical surface positive lens of plane-convex shape having a convex surface facing to the object side, a positive lens of biconvex shape, and a positive meniscus lens having a concave surface facing to the image side.

[0511] In this example, by using seven aspherical surface lenses, an optical system of large numerical aperture (NA) is provided with a lens number of 15 (fifteen).

[0512] As an alternative form, all the aspherical surface lenses may have a plane surface at a side opposite to the aspherical surface thereof.

(Example 23)

[0513] Figure 73 shows Numerical Example 24 which differs from Numerical Examples 20 - 23 in that, among aspherical surface lenses, there is at least one lens (bi-aspherical surface lens) having aspherical surfaces on both faces thereof.

[0514] In this example, all six aspherical surface lenses used are bi-aspherical surface lenses.

[0515] The lens optical system uses seven aspherical surfaces. Table 24 shows values corresponding to conditions of equations (2), (3) and (1). Figure 75 shows aberrations, and Figure 74 shows changes in local curvature power of the aspherical surface.

[0516] Details of the lens structure will be described below.

[0517] The first lens group L1 comprises, in an order from the object side, a bi-aspherical surface positive lens of approximately plane-convex shape having a convex surface facing to the object side. The aspherical surface at r1 includes a region in which the local curvature power changes in the positive direction, thus satisfying the function defined by condition (c3) described above. Also, in the relation with the surface r2, there are regions in which the local curvature powers change in mutually opposite directions, and the function of condition (c1) described above is satisfied.

[0518] The second lens group L2 comprises, in an order from the object side, a positive lens of meniscus shape having a concave surface facing to the image side, a bi-aspherical surface negative lens of biconcave shape, and a negative lens of approximately plane-concave shape having a concave surface facing to the object side.

[0519] The aspherical surface at r3 includes a region in which the local curvature power changes in the negative direction, thus satisfying the function defined by condition (c2) described above. Also, in the relation with the surface r4, there are regions in which their local curvature powers change in mutually opposite directions. Thus, also the function defined by condition (c1) described above is satisfied. Further, in the relation with the surface r6 of the second lens group L2, it is seen that there are regions in which their local curvature powers change in mutually opposite directions.

[0520] Further, in the aspherical surface r1 of the first lens group L1 and the aspherical surfaces r3 and r4 of the second lens group L2, at the peripheral portions the local curvature powers change in mutually opposite directions.

[0521] The third lens group L3 comprises, in an order from the object side, a bi-aspherical surface positive lens of approximately plane-convex shape having a convex surface facing to the image side, and a positive lenses of meniscus shape having a concave surface facing to the image side.

[0522] The fourth lens group L4 comprises, in an order from the object side, a bi-aspherical surface negative lens of biconcave shape, and a negative lens of biconcave shape.

[0523] The fifth lens group L5 comprises, in order from the object side, a positive lens of biconvex shape, a bi-aspherical surface positive lens of biconvex shape, a positive lens of meniscus shape having a concave surface facing

to the image side, and a bi-aspherical surface positive lens of meniscus shape having a concave surface facing to the image side.

[0524] In this example, by using six bi-aspherical surface lenses, an optical system of large numerical aperture (NA) is provided with a lens number of 13 (thirteen).

[0525] In this example, all the aspherical surface lenses in the lens optical system are bi-aspherical surface lenses each having aspherical surfaces on both faces thereof. However, this is not always necessary an aspherical surface lens having a spherical surface on a side opposite to the aspherical surface thereof may be used.

[0526] Further, an aspherical surface lens having a plane surface on a side opposite to the aspherical surface thereof may be included, singly or in combination with an aspherical surface lens having a spherical surface on a side opposite to the aspherical surface thereof.

[0527] This example uses six bi-aspherical surface lenses. However, the number of lenses is not limited to this. The lens number may be changed in accordance with aberration correction in the optical system being designed.

[0528] The conical constant k regarding the aspherical surface shape is taken as zero, in some examples of the examples described above. However, the aspherical surface shape may be designed while taking the conical constant k as a variable.

[0529] Further, in these examples except Numerical Example 21, silica is used as a lens glass material. However, fluorite may be used. When both silica and fluorite are used, chromatic aberration can be corrected to be very small.

[0530] For better imaging performance, additional aspherical surfaces may be used. Particularly, adding an aspherical surface satisfying conditions (2) and (3) between the object and the stop, is very effective to correct distortion and curvature of field, for example successfully.

[0531] In these examples, the exposure light source uses KrF wavelength of 248 nm or ArF wavelength of 193 nm. However, any other wavelength such as F_2 laser wavelength, for example, may be used. Also, the magnification of the projection optical system is not limited to 1:4 in these examples. Any other magnification may be used.

[0532] As described above, with use of aspherical surfaces, the number of lenses can be reduced considerably and, yet, a projection optical system having a large numerical aperture is accomplished.

[0533] When a face of an aspherical surface lens at a side opposite to the aspherical surface thereof is made a plane surface, a projection optical system being easy in manufacture and adjustment is provided. When the face at a side opposite to the aspherical surface is made a spherical surface, the degree of freedom can be expanded significantly, and better aberration correction is attainable.

[Examples 25 - 28]

[0534] Numerical Examples 25 - 28 to be described below concern a projection optical system having a seven-group structure. In these examples, the projection optical system comprises, in an order from the object side, a first lens group L1 having a positive refractive power, a second lens group L2 having a negative refractive power, a third lens group L3 having a positive refractive power, a fourth lens group L4 having a negative refractive power, a fifth lens group L5 having a positive refractive power, a sixth lens group L6 having a negative refractive power, and a seventh lens group L7 having a positive refractive power. Aspherical surfaces are formed on appropriate surfaces, whereby a good optical performance is obtained.

[0535] This projection optical system includes three lens groups having a negative refractive power. By distributing a strong negative refractive power in the lens optical system into these three lens groups, good correction of the Petzval sum is enabled. Also, an optical system of shorter total length can be accomplished.

[0536] Next, important features of lens structures of projection optical systems according to Numerical Examples 25 - 28 of the present invention will be described. In these examples, the projection optical system is made substantially telecentric on the object side (reticle side) and on the image plane side (wafer side). It has a projection magnification $\beta = 1:4$, a numerical aperture $NA = 0.65$, and an object-to-image distance (from object plane to image plane) $L = 1000$ mm. The reference wavelength is 193 nm. As regards the picture plane range, the diameter of an exposure area on a wafer is $\varnothing 27.3$ mm.

[0537] In Figures 77, 80, 83 and 86, the axis of ordinate represents the height of aspherical surface from the optical axis, being standardized with respect to the effective diameter, and the axis of abscissa denotes the aspherical surface number. The leftward and rightward directions correspond to negative and positive directions of the change in local curvature power, respectively.

(Example 25)

[0538] In Numerical Example 25 shown in Figure 76, the lens system comprises, in an order from the object side, a first lens group L1 having a positive refractive power, a second lens group L2 having a negative refractive power, a third lens group L3 having a positive refractive power, a fourth lens group L4 having a negative refractive power, a fifth

lens group L5 having a positive refractive power, a sixth lens group L6 having a negative refractive power, and a seventh lens group L7 having a positive refractive power.

[0539] The lens optical system uses seven aspherical surfaces. Table 25 shows values corresponding to conditions of equations (1), (2) and (3). Figure 78 shows aberrations, and Figure 77 shows changes in local curvature power of the aspherical surface.

[0540] Details of the lens structure will be described below.

[0541] The first lens group L1 comprises an aspherical surface positive lens of plane-convex shape, singly, having a convex surface facing to the image plane side.

[0542] The aspherical surface at r2 includes a region in which the local curvature power changes in the positive direction, satisfying the function of (c3) described above. With this aspherical surface, mainly a positive distortion is produced to contribute correction of distortion aberration.

[0543] The second lens group L2 comprises an aspherical surface negative lens of biconcave shape, singly.

[0544] The aspherical surface at r3 includes a region in which the local curvature power changes in the negative direction, satisfying the function of condition (c2) described above. Also, in the relation with the surface r2 of the first lens group L1, there are regions in which the local curvature powers change in mutually opposite directions, thus satisfying the function of condition (c1).

[0545] The third lens group L3 comprises, in an order from the object side, a positive lens of plane-convex shape having a convex surface facing to the image side, and an aspherical surface positive lens of approximately plane-convex shape having a convex surface facing to the object side.

[0546] The fourth lens group L4 comprises, in an order from the object side, a negative lens of biconcave shape, and an aspherical surface negative lens of biconcave shape. The aspherical surface at r11 includes a region in which the local curvature power changes in the negative direction, satisfying the function of condition (c2) described above. Also, in the relation with the surface r2 of the first lens group L1, there are regions in which the local curvature powers change in mutually opposite directions, thus satisfying the function of condition (c1). This aspherical surface is mainly contributable to good balance correction of image plane and comma aberration, for example.

[0547] The fifth lens group L5 comprises, in an order from the object side, a positive lens of approximately plane-convex shape having a convex surface facing to the image side, and a positive lens of biconvex shape.

[0548] The sixth lens group L6 comprises an aspherical surface negative lens of biconcave shape, singly. This aspherical surface is contributable mainly to correction of spherical aberration and comma aberration to be produced by a strong negative refractive power.

[0549] The seventh lens group L7 comprises, in an order from the object side, a positive lens of meniscus shape having a convex surface facing to the image side, an aspherical surface positive lens of biconvex shape, a positive lens of approximately plane-convex shape having a convex surface facing to the object side, two positive lenses of meniscus shape having a convex surface facing to the object side, a negative lens of meniscus shape having a concave surface facing to the image side, and a positive lens of meniscus shape having a convex surface facing to the object side.

[0550] In the seventh lens group, an aspherical surface is placed at a position where an axial light flux, which is a light flux emitted from an optical axis upon the object plane, is high, and this aspherical surface is used mainly for correction of negative spherical aberration to be produced in the seventh lens group having a strong positive refractive power. The aspherical surface used at a convex surface adjacent to the image plane is mainly contributable to correction of comma and distortion.

[0551] By introducing at least one aspherical surface satisfying the condition (3) into the lens optical system, as described above, the effect of using an aspherical surface sufficiently functions in providing an optical system of large numerical aperture.

[0552] Particularly, placing five aspherical surfaces before the stop of the lens optical system is effective for good balance correction of distortion aberration, astigmatism and comma, for example. Further, an aspherical surface is formed on a surface which satisfies the condition (2), that is, a surface which is very influential to the abaxial chief rays. With this arrangement, mainly the aberration related to abaxial rays is corrected on one hand, and the load for correction of other aberration is reduced on the other hand, by which a good optical performance is accomplished.

[0553] In this example, the aspherical surfaces which satisfy the condition (2) are surfaces at r2, r3, r7 and r11. Further, when an aspherical surface satisfying at least one of the conditions (c1) and (c2) described above is introduced, the effect of aspherical surface is enhanced and better aberration correction is attainable.

[0554] This example uses seven aspherical surfaces, and an optical system of large numerical aperture (NA) is provided with a lens number of 16 (sixteen).

(Example 26)

[0555] In Numerical Example 26 shown in Figure 79, the lens optical system uses seven aspherical surfaces. Table 26 shows values corresponding to conditions of equations (1), (2) and (3). Figure 81 shows aberrations, and Figure 80

shows changes in local curvature power of the aspherical surface.

[0556] Details of the lens structure will be described below.

[0557] The first lens group L1 comprises an aspherical surface positive lens of plane-convex shape, singly, having a convex surface facing to the image plane side.

5 [0558] The aspherical surface at r2 includes a region in which the local curvature power changes in the positive direction, satisfying the function of (c3) described above.

[0559] The second lens group L2 comprises an aspherical surface negative lens of biconcave shape, singly.

[0560] The aspherical surface at r3 includes a region in which the local curvature power changes in the negative direction, satisfying the function of condition (c2) described above. Also, in the relation with the surface r2 of the first lens group L1, there are regions in which the local curvature powers change in mutually opposite directions, thus satisfying the function of condition (c1).

[0561] The third lens group L3 comprises, in an order from the object side, a positive lens of plane-convex shape having a convex surface facing to the image side, and an aspherical surface positive lens of approximately plane-convex shape having a convex surface facing to the object side.

15 [0562] The fourth lens group L4 comprises, in an order from the object side, a negative lens of biconcave shape, and an aspherical surface negative lens of biconcave shape.

[0563] The fifth lens group L5 comprises three positive lenses of biconvex shape.

[0564] The sixth lens group L6 comprises an aspherical surface negative lens of biconcave shape, singly.

20 [0565] The seventh lens group L7 comprises, in an order from the object side, a positive lens of meniscus shape having a convex surface facing to the image side, an aspherical surface positive lens of biconvex shape, a positive lens of approximately plane-convex shape having a convex surface facing to the object side, two positive lenses of meniscus shape having a convex surface facing to the object side, a negative lens of meniscus shape having a concave surface facing to the image side, and an aspherical surface positive lens of meniscus shape having a convex surface facing to the object side.

25 [0566] This example uses seven aspherical surfaces, and an optical system of large numerical aperture (NA) is provided with a lens number of 17 (seventeen).

(Example 27)

30 [0567] Figure 82 shows a projection optical system according to Numerical Example 27 of the present invention. Table 27 shows values corresponding to conditions of equations (1), (2) and (3). Figure 84 shows aberrations, and Figure 83 shows changes in local curvature power of the aspherical surface. This lens system uses eight aspherical surfaces, and the values corresponding to equation (3) are shown in Table 27.

[0568] In this example, all the aspherical surface lens have a plane surface on a side opposite to the aspherical surface thereof.

35 [0569] Details of the lens structure will be described below.

[0570] The first lens group L1 comprises, in an order from the object side, an aspherical surface positive lens of plane-convex shape having a convex surface facing to the image plane side, and a positive lens of biconvex shape.

40 [0571] The aspherical surface at r2 includes a region in which the local curvature power changes in the negative direction.

[0572] The second lens group L2 comprises, in an order from the object side, two aspherical surface negative lenses of plane-concave shape having a concave surface facing to the image side.

[0573] The aspherical surfaces at r4 and r6 include regions in which the local curvature powers change in the positive direction. Also, in the relation with the surface r2 of the first lens group L1, both of the surfaces r4 and r6 include regions in which the local curvature powers change in mutually opposite directions, thus satisfying the function of condition (c1).

45 [0574] The third lens group L3 comprises, in an order from the object side, an aspherical surface positive lens of plane-convex shape having a convex surface facing to the image side, and a positive lens of biconvex shape. The aspherical surface r10 includes a region in which the local curvature power changes in the negative direction, thus satisfying the function of condition (c3) described above.

50 [0575] The fourth lens group L4 comprises, in an order from the object side, a negative lens of meniscus shape having a concave surface facing to the image side, a negative lens of biconcave shape, and an aspherical surface negative lens of plane-concave shape having a concave surface facing to the object side. The aspherical surface at r17 includes a region in which the local curvature power changes in the negative direction, satisfying the function of condition (c2) described above. Also, in the relation with the surface r10 of the third lens group L3, there are regions in which the local curvature powers change in mutually opposite directions, thus satisfying the function of condition (c1).

55 [0576] The fifth lens group L5 comprises, in an order from the object side, a positive lens of meniscus shape having a concave surface facing to the object side, a positive lens of biconvex shape, and an aspherical surface positive lens

of plane-convex shape having a convex surface facing to the object side.

[0577] The sixth lens group L6 comprises two negative lenses of biconcave shape.

[0578] The seventh lens group L7 comprises, in an order from the object side, an aspherical surface positive lens of plane-convex shape having a convex surface facing to the image side, two positive lenses of biconvex shape, a positive lens of meniscus shape having a concave surface facing to the image side, and an aspherical surface positive lens of plane-convex shape having a convex surface facing to the object side.

[0579] This example uses eight aspherical surfaces, and an optical system of large numerical aperture (NA) is provided with a lens number of 19 (nineteen).

(Example 28)

[0580] Figure 85 shows a projection optical system according to Numerical Example 28 of the present invention. Table 28 shows values corresponding to conditions of equations (1), (2) and (3). Figure 87 shows aberrations, and Figure 86 shows changes in local curvature power of the aspherical surface.

[0581] This lens system uses nine aspherical surfaces. More specifically, three bi-aspherical surface lenses (each having two aspherical surface on both faces thereof) and three mono-aspherical surface lenses each having a spherical surface on a side opposite to the aspherical surface thereof. Thus, six aspherical surface lenses with nine aspherical surfaces in total are used.

[0582] Details of the lens structure will be described below.

[0583] The first lens group L1 comprises, in an order from the object side, a positive lens of approximately plane-convex shape having a convex surface facing to the image plane side, and a positive lens of biconvex shape.

[0584] The aspherical surface at r3 includes a region in which the local curvature power changes in the positive direction, thus satisfying the function defined in condition (c3) described above.

[0585] The second lens group L2 comprises, in an order from the object side, an aspherical surface negative lens of biconcave shape, and a negative lens of biconcave shape.

[0586] The aspherical surfaces at r5 and r6 include regions in which the local curvature powers change in the negative direction, and the function of condition (c2) described above is satisfied. Also, there is a region in which, relative to the aspherical surface r3 of the first lens group L1, the local curvature powers change with mutually opposite signs to cancel with each other. Thus, the function of condition (c1) described above is satisfied. Further, between the surfaces r5 and r6, the local curvature powers of them, at the peripheral portion thereof, change with mutually opposite signs to cancel with each other.

[0587] The third lens group L3 comprises, in an order from the object side, a positive lens of meniscus shape having a concave surface facing to the object side, and an aspherical surface positive lens of biconvex shape. The aspherical surface r11 includes a region in which the local curvature power changes in the positive direction, thus satisfying the function of condition (c3) described above.

[0588] The fourth lens group L4 comprises, in an order from the object side, a negative lens of meniscus shape having a concave surface facing to the image side, and two negative lenses of biconcave shape.

[0589] The fifth lens group L5 comprises, in an order from the object side, a positive lens of approximately plane-convex having a convex surface facing to the image side, an aspherical surface positive lens of biconvex shape, and a positive lens of approximately plane-convex shape having a convex surface facing to the object side.

[0590] The sixth lens group L6 comprises, in an order from the object side, a negative lens of approximately plane-convex shape having a concave surface facing to the image side, and a negative lenses of biconcave shape.

[0591] The seventh lens group L7 comprises, in an order from the object side, a positive lens of biconvex shape, an bi-aspherical surface positive lens of biconvex shape, two positive lenses of meniscus shape having a concave surface facing to the image side, and a bi-aspherical surface positive lens of meniscus shape having a concave surface facing to the image side.

[0592] This example uses three bi-aspherical surface lenses (each having two aspherical surfaces on both faces thereof) and three mono-aspherical surface lenses (each having a spherical surface on a side opposite to the aspherical surface thereof), and an optical system of large numerical aperture (NA) is provided with a lens number of 19 (nineteen).

[0593] For better imaging performance, additional aspherical surfaces may be used. Particularly, adding an aspherical surface satisfying condition (3) between the object and the stop, is very effective to correct distortion and curvature of field, for example successfully. When it is added in a lens group after the stop, further improvements in various aberrations such as spherical aberration and comma, are attainable.

[0594] As described above, with use of aspherical surfaces, the number of lenses can be reduced considerably and, yet, a projection optical system having a large numerical aperture is accomplished.

[0595] When a face of an aspherical surface lens at a side opposite to the aspherical surface thereof is made a plane surface, a projection optical system being easy in manufacture and adjustment is provided. When the face at a

side opposite to the aspherical surface is made a spherical surface, the degree of freedom can be expanded significantly, and better aberration correction is attainable.

[0596] The conical constant k regarding the aspherical surface shape is taken as zero, in some examples of Numerical Examples 1 - 28 described above. However, the aspherical surface shape may be designed while taking the conical constant k as a variable.

[0597] Further, in some examples described above, silica ($n = 1.5602$) is used as a lens glass material. However, fluorite may be used. When both silica and fluorite are used, chromatic aberration can be corrected to be very small.

[0598] In many of these examples, the exposure light source uses an ArF wavelength laser of 193 nm (h-line in Example 17). However, any other wavelength shorter than 250 nm, such as KrF excimer laser (wavelength 248 nm) or F₂ laser (wavelength 157 nm), for example, may be used. Also, the magnification of the projection optical system is not limited to 1:4 in these examples. Any other magnification such as 1:5, for example, may be used.

[0599] Next, structural specifications of these numerical examples will be described. In the numerical example data to be described below, "ri" refers to the curvature radius of the i-th lens surface, in an order from the object side, and "di" refers to the i-th lens thickness or air spacing, in an order from the object side. Further, "ni" refers to the refractive index of the glass material of the i-th lens lens, in an order from the object side.

[0600] The shape of an aspherical surface can be given by the following equation:

$$X = \frac{H^2/ri}{1 + \{1 - (1+k) \cdot (H/ri)^2\}^{1/2}} + A \cdot H^4 + B \cdot H^6 + C \cdot H^8 + D \cdot H^{10} + E \cdot H^{12} + F \cdot H^{14} + G \cdot H^{16} + \dots$$

where X is the displacement amount in the optical axis direction from the lens vertex, H is the distance from the optical axis, ri is the curvature radius, k is the conical constant, and A, B, C, \dots, G are aspherical coefficients.

[0601] The refractive indices of fused silica and fluorite with respect to the exposure wavelength 193 nm are 1.5602 and 1.5014, respectively.

[0602] Further, the local curvature power of an aspherical surface referred to in the specification is given as a function $X(H)$ of X and H in the above equation, by the following:

$$PH = (N' - N)/\rho$$

where

$$\rho = (1 + X'^2)^{3/2}/X''$$

wherein N and N' are refractive indices of mediums before and after the refraction surface.

[0603] The following are numerical data for Numerical Examples 1 - 28. Also, Tables 1 - 28 below show the relation between the conditions described above and these numerical examples.

[Numerical Example 1]

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i	ri	di	ni	Obj-distance= 70.000
1	7563.434	11.000	1.50140	
2	251.917	17.200		
3	-2311.851	38.151	1.56020	
4	-271.421	7.945		
5	334.300	33.453	1.56020	
6	-219.013	1.000		
7	173.820	17.822	1.56020	
8	472.228	1.000		
9	166.425	20.537	1.50140	
ASP10	92.001	26.942		
11	-492.808	47.000	1.56020	
ASP12	539.947	53.772		
13	-87.519	11.000	1.56020	
14	183.967	23.005		
15	-92.489	11.000	1.56020	
16	-1991.709	38.780		
17	5589.217	33.160	1.56020	
18	-210.728	1.000		
19	19670.824	26.317	1.50140	
ASP20	-278.596	1.000		
21	459.320	42.261	1.50140	
22	-419.941	199.293		
ASP23	262.924	28.089	1.50140	
24	1496.662	37.244		
ASP25	202.338	31.685	1.50140	
26	1192.437	1.000		
27	194.380	27.820	1.50140	
28	605.386	6.888		
29	170.010	29.602	1.56020	
30	243.002	8.981		
31	196.503	18.733	1.56020	
32	141.592	27.827		
ASP33	205.568	13.490	1.56020	
34	405.138			

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aspherical surfaces

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i	K	A	B	C	D
10	-7.924169e-002	-3.355354e-008	-8.165025e-012	-1.282327e-015	-3.015911e-019
12	0.000000e+000	-2.702105e-008	8.731564e-012	1.171736e-015	5.514590e-019
20	-1.689089e-001	2.282695e-008	2.768267e-013	4.557746e-019	-7.785683e-023
23	1.549976e-003	-3.488190e-009	-5.892913e-013	6.390236e-018	-3.718856e-022
25	-7.080562e-002	-2.442717e-008	1.674842e-013	-5.964801e-018	1.311802e-022
33	-6.457308e-001	5.114130e-008	1.559426e-011	-1.398483e-015	5.607100e-019

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i	E	F	G
10	1.508201e-023	-1.215145e-026	0.000000e+000
12	-1.037663e-022	3.178927e-026	0.000000e+000
20	6.124503e-028	3.667262e-032	0.000000e+000
23	8.770095e-027	-1.683943e-031	0.000000e+000
25	-1.028257e-026	1.440202e-032	0.000000e+000
33	-1.181280e-022	1.258643e-026	0.000000e+000

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NA = 0.65

 $\beta = 1/4$

L = 1000

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[Numerical Example 2]

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	i	ri	di	ni	Obj-distance= 70.000
	1	∞	11.000	1.56020	
ASP	2	241.465	89.729		
	3	259.326	33.985	1.56020	
	4	-721.262	16.736		
ASP	5	839.101	13.458	1.56020	
	6	∞	8.787		
	7	160.242	33.590	1.56020	
	8	1214.104	22.148		
	9	129.280	19.364	1.56020	
	10	174.248	47.364		
ASP	11	-141.760	11.000	1.56020	
	12	908.569	8.936		
	13	-164.780	11.000	1.56020	
	14	93.667	21.167		
ASP	15	-132.458	47.000	1.56020	
	16	∞	11.171		
	17	5830.851	43.946	1.56020	
	18	-344.819	37.984		
	19	568.585	30.551	1.50140	
ASP	20	-294.579	20.971		
	21	899.021	24.198	1.50140	
	22	-473.709	140.955		
ASP	23	340.419	22.918	1.50140	
	24	∞	1.000		
	25	228.928	31.111	1.50140	
	26	2032.762	1.000		
ASP	27	216.729	29.615	1.50140	
	28	745.891	1.000		
	29	146.642	47.000	1.56020	
	30	521.804	5.774		
	31	∞	16.697	1.56020	
ASP	32	1397.306	4.364		
ASP	33	-595.584	30.479	1.56020	
	34	∞			

aspherical surfaces

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i	K	A	B	C	D
2	0.00000e+000	-8.899777e-008	4.468913e-012	-6.084916e-017	-1.783704e-022
5	0.00000e+000	9.842755e-009	4.892032e-013	-6.747952e-018	-8.110711e-022
11	0.00000e+000	-1.355522e-007	3.004930e-011	2.019333e-015	-6.833401e-019
15	0.00000e+000	-7.518484e-008	-8.479227e-012	-1.320534e-015	6.990086e-020
20	0.00000e+000	1.759961e-008	1.555047e-013	-4.699964e-019	-5.339673e-023
23	0.00000e+000	-1.206905e-008	-2.262720e-013	9.284450e-018	1.832386e-022
27	0.00000e+000	6.500841e-009	1.034536e-013	-1.828330e-017	-1.247995e-021
32	0.00000e+000	-1.844592e-008	1.601803e-012	-8.642931e-016	-2.787101e-019
33	0.00000e+000	4.100318e-008	7.653147e-012	-2.748195e-015	1.526792e-019

i	E	F	G
2	7.421051e-025	0.000000e+000	0.000000e+000
5	9.181608e-027	0.000000e+000	0.000000e+000
11	4.876491e-023	0.000000e+000	0.000000e+000
15	-4.950373e-023	0.000000e+000	0.000000e+000
20	-2.680910e-027	0.000000e+000	0.000000e+000
23	-9.584813e-027	0.000000e+000	0.000000e+000
27	-4.922083e-026	0.000000e+000	0.000000e+000
32	5.616870e-023	0.000000e+000	0.000000e+000
33	1.903938e-023	0.000000e+000	0.000000e+000

$$NA = 0.65$$

$$\beta = 1/4$$

$$L = 1000$$

[Numerical Example 3]

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	i	ri	di	ni	Obj-distance= 78.337
	1	∞	11.000	1.56020	
ASP	2	291.960	13.576		
	3	-2468.391	18.430	1.56020	
	4	-212.937	2.174		
	5	632.275	36.661	1.56020	
	6	-195.510	1.716		
ASP	7	209.897	30.803	1.56020	
	8	∞	10.964		
	9	179.370	11.379	1.56020	
	10	85.411	36.359		
	11	∞	9.310	1.56020	
ASP	12	137.626	70.188		
	13	-94.815	9.310	1.56020	
	14	354.874	22.479		
	15	-94.483	10.344	1.56020	
	16	-819.857	20.429		
	17	-1867.588	33.299	1.56020	
	18	-217.001	1.000		
	19	∞	40.000	1.56020	
ASP	20	-234.059	1.000		
	21	477.242	37.938	1.56020	
	22	-515.192	207.111		
ASP	23	298.270	48.200	1.56020	
	24	∞	11.674		
ASP	25	275.687	36.978	1.56020	
	26	∞	10.799		
	27	203.097	32.137	1.56020	
	28	633.727	2.293		
	29	186.253	28.417	1.56020	
	30	1012.907	5.512		
	31	1325.581	18.749	1.56020	
	32	107.474	22.379		
ASP	33	180.126	18.257	1.56020	
	34	∞			

aspherical surfaces

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i	X	A	B	C	D
2	0.000000e+000	3.736230e-008	1.038222e-012	-3.965564e-016	-5.505777e-021
7	0.000000e+000	4.848022e-009	4.158133e-012	1.071518e-016	-2.266750e-021
12	0.000000e+000	-1.028517e-007	1.142371e-011	1.548505e-015	3.030974e-019
20	0.000000e+000	2.096099e-008	1.467669e-013	2.256954e-018	-4.666722e-023
23	0.000000e+000	-1.621224e-009	-5.579396e-013	7.419379e-018	-3.142413e-022
25	0.000000e+000	-2.374554e-008	3.141420e-013	-2.583907e-018	8.955907e-023
33	0.000000e+000	6.812835e-008	5.847001e-012	-1.362069e-017	8.105142e-020

i	E	F	G
2	3.907528e-024	-2.229541e-028	0.000000e+000
7	7.709364e-025	-4.176635e-029	0.000000e+000
12	-8.699782e-024	1.590852e-026	0.000000e+000
20	-1.190790e-027	8.053524e-032	0.000000e+000
23	7.943315e-027	-9.396981e-032	0.000000e+000
25	-8.404456e-027	7.322317e-032	0.000000e+000
33	-1.014027e-023	8.198208e-028	0.000000e+000

$$NA = 0.65$$

$$\beta = 1/4$$

$$L = 1000$$

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[Numerical Example 4]

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i	ri	di	ni	Obj-distance= 94.777
1	-211.935	25.002	1.56020	
2	-274.973	34.686		
3	921.019	19.213	1.56020	
4	-878.587	1.375		
5	310.870	29.825	1.56020	
6	-410.625	1.000		
ASP 7	162.868	29.679	1.56020	
ASP 8	719.157	37.255		
ASP 9	-694.335	8.000	1.56020	
ASP 10	151.022	45.485		
11	-212.339	10.002	1.56020	
12	510.245	34.725		
13	-64.375	8.000	1.56020	
14	278.092	60.268		
15	1461.988	41.610	1.56020	
16	-189.700	1.000		
17	5371.657	28.376	1.56020	
ASP 18	-311.325	1.649		
19	312.645	39.189	1.56020	
20	305.130	112.761		
21	385.134	42.570	1.56020	
22	-1353.684	65.759		
ASP 23	210.713	45.920	1.56020	
24	-7100.101	1.172		
25	161.697	40.777	1.56020	
26	672.543	24.705		
27	-2434.070	10.000	1.56020	
28	257.881	1.113		
ASP 29	203.124	37.891	1.56020	
ASP 30	2059.555			

aspherical surfaces

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i	K	A	B	C	D
7	6.495603e-001	1.625859e-008	1.741255e-013	-1.414452e-017	1.744975e-020
8	0.000000e+000	6.098222e-009	-2.569543e-012	2.225990e-016	8.493683e-020
9	0.000000e+000	-5.436344e-008	1.105804e-011	5.667300e-015	-3.480729e-019
10	8.962335e-001	3.597303e-008	1.251516e-011	5.836732e-015	1.516663e-020
18	2.384810e-001	1.556881e-008	1.678934e-013	-7.371860e-019	1.581607e-022
23	5.623844e-002	-1.320180e-008	-4.292778e-013	-8.709804e-018	-3.927143e-023
29	0.000000e+000	-5.318060e-008	5.315370e-012	4.059718e-016	-3.209172e-020
30	0.000000e+000	-2.730145e-008	6.579062e-012	7.288556e-017	-3.648637e-019

i	E	F	G
7	4.363123e-025	9.563679e-028	-1.965524e-033
8	7.645759e-024	-5.447221e-028	-7.558589e-032
9	-1.501620e-022	3.645460e-028	1.529071e-030
10	-2.368293e-022	1.602413e-026	-1.126581e-029
18	-1.625511e-026	8.891181e-031	-1.806298e-035
23	-6.738671e-027	2.324125e-031	-7.432070e-036
29	-6.309136e-024	1.135376e-027	-5.838246e-032
30	8.493168e-023	-9.227818e-027	4.009184e-031

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$NA = 0.65$
 $\beta = 1/4$
 $L = 1000$

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[Numerical Example 5]

i				ni	Obj-distance= 76.729
	ri	di			
1	∞	10.630	1.56020		
2	262.778	21.348			
3	-2352.332	24.105	1.56020		
4	-215.727	3.497			
5	335.785	34.929	1.56020		
6	-219.548	1.210			
ASP 7	174.011	30.803	1.56020		
ASP 8	223.533	58.374			
ASP 9	-721.643	9.310	1.56020		
ASP 10	117.483	67.811			
11	-72.728	9.310	1.56020		
12	2719.240	25.453			
13	-98.805	10.344	1.56020		
14	-727.917	19.799			
15	-988.788	34.866	1.56020		
16	-181.841	1.000			
ASP 17	-63212.427	38.888	1.56020		
ASP 18	-248.015	1.000			
19	652.250	39.209	1.56020		
20	-381.746	204.164			
ASP 21	237.211	51.746	1.56020		
ASP 22	-534.246	11.973			
23	175.589	33.761	1.56020		
24	457.536	2.163			
25	173.823	45.901	1.56020		
26	104.356	22.473			
ASP 27	183.135	47.090	1.56020		
ASP 28	-18395.030				

aspherical surfaces

i						
	K	A	B	C	D	
7	0.000000e+000	2.602087e-008	-9.861657e-013	1.543773e-016	1.406696e-020	
8	0.000000e+000	-4.996999e-009	-7.964895e-012	3.960131e-016	2.894002e-019	
9	0.000000e+000	-9.044863e-008	1.795894e-011	1.168555e-014	-1.916381e-019	
10	0.000000e+000	-9.122145e-008	2.638650e-011	1.484569e-014	-3.164586e-019	
17	0.000000e+000	-2.313834e-009	4.775923e-013	-1.219135e-017	-8.487163e-022	
18	0.000000e+000	1.619892e-008	6.583868e-013	5.134005e-018	-1.010584e-023	
21	0.000000e+000	-2.460447e-008	-8.025827e-014	6.851226e-019	-6.974895e-023	
22	0.000000e+000	4.392679e-009	1.790428e-013	-3.316430e-018	-7.037122e-023	
27	0.000000e+000	6.116374e-009	1.014227e-011	-1.144411e-016	-1.547734e-019	
28	0.000000e+000	-3.758336e-008	2.767725e-011	-1.049151e-014	2.230695e-018	
i						
	E	F	G			
7	8.828934e-024	6.065203e-029	0.000000e+000			
8	8.277960e-024	0.000000e+000	0.000000e+000			
9	-1.939457e-022	0.000000e+000	0.000000e+000			
10	1.549810e-022	1.589349e-026	0.000000e+000			
17	2.904456e-026	0.000000e+000	0.000000e+000			
18	-7.201050e-026	2.156004e-030	0.000000e+000			
21	-8.626227e-027	8.632202e-032	0.000000e+000			
22	-2.921158e-028	0.000000e+000	0.000000e+000			
27	2.856544e-023	-1.501637e-027	0.000000e+000			
28	-2.036412e-022	0.000000e+000	0.000000e+000			

$$NA = 0.65$$

$$\beta = 1/4$$

$$L = 979$$

[Numerical Example 6]

5 i ri di ni Obj-distance= 105.380

1 615.988 18.534 1.50850

2 -383.644 0.100

3 286.397 18.564 1.50850

4 -1437.441 0.100

5 190.097 19.857 1.50850

6 2853.160 0.100

7 178.185 11.000 1.50850

10 8 107.105 13.672

9 142.973 16.425 1.50850

10 118.870 16.687

11 -500.224 11.208 1.50850

12 167.322 28.182

ASP13 -214.604 11.000 1.50850

14 250.009 20.509

15 15 -159.879 11.031 1.50850

16 -871.412 12.466

17 -281.698 15.983 1.50850

18 -172.061 1.263

19 1567.676 28.605 1.50850

20 -230.841 0.100

21 2957.023 25.135 1.50850

22 -317.075 0.100

23 743.070 25.712 1.50850

24 -460.817 0.100

25 208.157 32.503 1.50850

26 -6943.879 0.421

27 242.340 33.909 1.50850

28 151.140 8.381

29 229.004 11.800 1.50850

30 147.331 29.645

31 -257.186 11.800 1.50850

32 198.612 31.653

33 -127.396 11.800 1.50850

34 1158.506 39.131

35 -561.270 19.932 1.50850

36 -228.783 43.324

37 4362.533 34.492 1.50850

38 -274.853 0.100

39 861.165 26.541 1.50850

40 -726.597 0.100

41 594.436 31.124 1.50850

42 -723.222 16.167

43 -311.276 25.000 1.50850

44 -393.499 0.100

45 238.968 34.553 1.50850

46 1417.673 0.100

47 162.808 31.997 1.50850

48 371.018 0.100

49 136.027 24.985 1.50850

50 230.317 13.522

51 563.294 11.001 1.50850

52 76.679 26.332

ASP53 85.289 58.676 1.50850

54 1259.907

NA= 0.65
 $\beta = 1/4$
L = 1050

aspherical surfaces

13 K A B C D

53 1.374337e+000 -1.584636e-008 1.916550e-012 -5.383453e-016 2.263367e-019

53 0.000000e+000 2.751100e-008 5.808228e-012 -1.354164e-017 6.184812e-019

13 E F G

53 -6.393124e-023 5.892181e-027 0.000000e+000

53 -1.508737e-022 2.672592e-026 0.000000e+000

[Numerical Example 7]

5

i	ri	di	ni	Obj-distance= 93.869
1	685.809	16.577	1.50850	
2	-441.006	0.100		
3	397.311	18.226	1.50850	
4	-571.011	0.138		
5	266.971	21.856	1.50850	
6	-5608.095	11.732		
7	305.587	27.236	1.50850	
8	99.728	17.460		
9	114008.101	14.287	1.50850	
ASP 10	111.532	24.508		
ASP 11	-203.639	11.000	1.50850	
12	262.585	19.913		
13	-149.755	11.000	1.50850	
14	-603.441	12.966		
15	-250.839	15.788	1.50850	
16	-170.460	2.110		
17	2105.855	28.463	1.50850	
18	-226.097	3.907		
19	1676.122	25.733	1.50850	
20	-328.306	0.100		
21	576.425	26.582	1.50850	
22	-512.315	3.154		
23	215.803	31.877	1.50850	
24	-4089.312	0.294		
25	243.970	33.267	1.50850	
26	143.075	8.148		
27	196.795	11.800	1.50850	
28	139.205	30.930		
29	-219.681	11.800	1.50850	
30	211.178	32.392		
31	-136.079	11.800	1.50850	
32	1362.342	39.659		
33	-486.992	20.686	1.50850	
34	-227.410	44.812		
35	13247.358	34.699	1.50850	
36	-270.597	0.100		
37	790.036	26.195	1.50850	
38	-869.446	0.100		
39	518.020	33.193	1.50850	
40	-780.408	16.284		
41	-327.775	25.000	1.50850	
42	-444.896	0.100		
43	266.574	36.001	1.50850	
44	5487.547	0.100		
45	147.257	35.230	1.50850	
46	313.243	0.100		
47	140.928	22.653	1.50850	
48	215.247	10.541		
49	430.568	11.000	1.50850	
50	84.708	26.961		
51	93.991	25.870	1.50850	
52	862.356	9.500		
53	-991.884	24.290	1.50850	
54	-731.263			

NA = 0.65

 $\beta = 1/4$

L = 1050

aspherical surfaces

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i	K	A	B	C	D
10	-2.717797e-001	-2.885201e-008	-6.026619e-013	-2.918385e-015	1.725616e-018
11	1.419563e+000	-1.167490e-008	4.045580e-012	-3.781544e-015	2.436852e-018

i	E	F	G
10	-5.375995e-022	7.517989e-026	0.000000e+000
11	-8.052133e-022	1.108873e-025	0.000000e+000

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[Numerical Example 8]

	i	r _i	d _i	n _i	Obj-distance= 94.486
5	1	337.003	22.211	1.50850	
	2	-355.093	0.100		
	ASP3	292.157	21.149	1.50850	
	ASP4	-560.057	0.100		
	5	521.242	20.958	1.50850	
	6	76436.568	14.385		
	7	818.454	16.035	1.50850	
10	8	97.900	17.606		
	ASP9	-1467.092	11.428	1.50850	
	ASR0	142.710	26.020		
	11	-212.403	11.196	1.50850	
	12	353.410	20.216		
	13	-134.210	11.240	1.50850	
	14	-1002.862	12.039		
15	15	-236.025	15.914	1.50850	
	16	-166.795	0.204		
	17	779.273	35.407	1.50850	
	18	-209.072	0.100		
	19	-1786.188	23.880	1.50850	
	ASP20	-273.517	0.100		
	21	826.670	19.862	1.50850	
20	22	-782.423	9.552		
	23	183.291	33.305	1.50850	
	24	864.185	1.121		
	25	189.560	33.969	1.50850	
	26	115.050	59.543		
	27	-247.564	11.800	1.50850	
	28	180.291	32.382		
25	29	-141.987	11.800	1.50850	
	30	1634.805	38.291		
	31	-432.625	19.180	1.50850	
	32	-225.869	43.366		
	33	-5580.889	36.257	1.50850	
	34	-251.752	0.100		
	ASP35	656.210	28.234	1.50850	
30	36	-1123.439	11.355		
	37	476.442	32.359	1.50850	
	38	-1813.445	21.067		
	39	285.017	37.448	1.50850	
	40	3204.814	0.416		
	41	153.457	38.178	1.50850	
	42	357.667	0.100		
35	43	144.612	27.813	1.50850	
	44	279.653	12.152		
	45	1408.031	15.899	1.50850	
	46	83.926	28.089		
	ASP47	98.536	31.980	1.50850	
	48	-5814.320			

$$NA = 0.65$$

$$\beta = 1/4$$

$$L = 1050$$

spherical surfaces

	i	K	A	B	C	D
40	3	-1.467540e+000	-8.951376e-009	-2.285210e-012	1.324945e-016	2.628948e-020
	4	0.000000e+000	-5.978443e-009	-1.682938e-012	7.478670e-016	-1.459628e-020
	9	0.000000e+000	-2.123929e-008	1.529902e-011	2.095313e-015	-9.109944e-019
	10	-2.064869e-001	-1.153015e-008	1.122575e-011	1.126785e-015	-1.300266e-018
45	20	0.000000e+000	2.186523e-009	9.742324e-014	4.751496e-018	6.448589e-023
	35	0.000000e+000	-7.201429e-010	1.483951e-016	-3.090615e-019	-3.685641e-024
	47	0.000000e+000	1.133753e-009	-6.956249e-014	1.466240e-016	-9.834080e-022
	i	E	F	G		
50	3	4.673713e-024	0.000000e+000	0.000000e+000		
	4	4.074521e-024	0.000000e+000	0.000000e+000		
	9	1.128762e-023	0.000000e+000	0.000000e+000		
	10	1.052897e-022	0.000000e+000	0.000000e+000		
	20	8.837182e-027	0.000000e+000	0.000000e+000		
	35	1.334447e-029	0.000000e+000	0.000000e+000		
	47	2.247095e-023	0.000000e+000	0.000000e+000		

[Numerical Example 9]

	i	ri	di	ni	Obj-distance= 98.214
	1	∞	16.704	1.56020	
	2	-299.434	1.000		
ASP	3	175.000	23.792	1.56020	
	4	∞	9.571		
	5	145.117	32.038	1.56020	
	6	100.000	17.662		
	7	∞	11.000	1.56020	
ASP	8	123.021	20.788		
	9	-161.438	11.000	1.56020	
	10	154.557	86.015		
	11	∞	35.660	1.56020	
ASP	12	-212.876	1.000		
	13	766.932	44.175	1.56020	
	14	-268.029	1.000		
	15	226.078	41.874	1.56020	
	16	-1378.930	61.794		
	17	∞	11.000	1.56020	
ASP	18	167.725	28.903		
	19	-181.282	11.000	1.56020	
	20	151.497	109.955		
	21	∞	26.211	1.56020	
ASP	22	-281.746	1.000		
	23	270.807	44.763	1.56020	
	24	-760.019	61.715		
ASP	25	272.524	29.142	1.56020	
	26	∞	1.000		
	27	160.854	31.901	1.56020	
	28	490.918	1.000		
	29	150.000	47.000	1.56020	
	30	139.001	12.403		
ASP	31	464.315	23.386	1.56020	
	32	∞			

$$NA = 0.65$$

$$\beta = 1/4$$

$$L = 1000$$

aspherical surfaces

i	K	A	B	C	D
3	0.000000e+000	3.765611e-008	1.857832e-013	2.140099e-017	-7.657000e-022
8	0.000000e+000	1.066079e-007	5.208923e-012	1.839063e-016	1.530801e-019
12	0.000000e+000	3.799718e-009	2.913747e-014	-1.192573e-018	3.790180e-022
18	0.000000e+000	-2.093220e-008	-3.107989e-012	-1.945659e-016	-1.455401e-020
22	0.000000e+000	1.011214e-008	2.021265e-013	9.016095e-018	2.046099e-022
25	0.000000e+000	-5.788514e-009	-3.819654e-013	8.070465e-019	-3.300433e-022
31	0.000000e+000	-5.149679e-008	-5.336959e-012	4.625129e-016	-1.392531e-020

i	E	F	G
3	4.433241e-025	-4.391693e-029	0.000000e+000
8	9.302962e-024	-5.916181e-027	0.000000e+000
12	-3.152611e-026	1.892071e-030	0.000000e+000
18	1.127026e-024	-1.445302e-028	0.000000e+000
22	3.329047e-027	3.174893e-031	0.000000e+000
25	7.913976e-027	-5.366459e-031	0.000000e+000
31	4.069475e-024	-4.957972e-028	0.000000e+000

[Numerical Example 10]

	i	ri	di	ni	Obj-distance= 98.214
	1	66506.430	20.534	1.56020	
	2	-200.815	1.000		
ASP	3	247.178	24.228	1.56020	
ASP	4	-1273.958	1.799		
	5	171.546	22.308	1.56020	
	6	98.980	17.896		
	7	1182.942	11.000	1.56020	
	8	159.619	19.222		
ASP	9	-182.740	11.000	1.56020	
ASP	10	207.068	86.213		
	11	500.819	43.015	1.56020	
	12	-240.019	1.000		
ASP	13	319.058	41.291	1.56020	
ASP	14	-365.817	1.000		
	15	229.840	28.376	1.56020	
	16	-8803.339	46.316		
	17	-264.505	11.000	1.56020	
	18	184.159	18.143		
ASP	19	-268.210	11.000	1.56020	
ASP	20	112.292	140.901		
ASP	21	1504.030	27.617	1.50140	
ASP	22	-325.199	1.000		
	23	287.965	37.520	1.50140	
	24	-1646.618	63.842		
ASP	25	291.973	40.105	1.50140	
ASP	26	-599.669	1.000		
	27	176.529	32.020	1.50140	
	28	557.997	1.000		
	29	120.000	47.000	1.56020	
	30	80.443	8.223		
	31	98.682	46.988	1.56020	
	32	164.043			

aspherical surfaces

i	K	A	B	C	D
3	-2.147054e+000	2.855743e-008	-1.036774e-012	1.275547e-016	4.593414e-020
4	0.000000e+000	1.336794e-008	-1.397714e-012	3.702893e-016	6.224425e-020
9	-2.089679e-001	1.000595e-008	7.735659e-012	1.330938e-016	3.122334e-019
10	1.063518e+000	1.481255e-008	1.699184e-012	5.097592e-016	4.237075e-020
13	-1.680764e+000	-5.776339e-009	-1.148440e-012	-2.490235e-017	-5.242060e-022
14	1.885960e+000	-7.212811e-009	-4.316706e-013	-2.408691e-017	1.071687e-022
19	-3.574249e+000	2.409944e-008	4.315636e-013	-3.840839e-016	1.186363e-019
20	9.429294e-002	-3.335778e-010	-1.425263e-011	-6.427809e-016	9.891739e-020
21	2.184806e+001	1.253508e-009	6.846267e-014	1.221954e-018	3.386655e-023
22	-5.933867e-003	1.096606e-008	1.175524e-013	5.758626e-018	1.039016e-022
25	-3.712593e-001	-8.843257e-009	-4.036554e-013	2.210059e-018	-1.172515e-022
26	-5.741502e+000	1.687149e-010	2.510453e-014	-2.894874e-018	1.807084e-022
i	E	F	G		
3	-9.393944e-025	1.747211e-027	0.000000e+000	$NA = 0.65$ $\beta = 1/4$ $L = 1000$	
4	1.068921e-026	1.806181e-027	0.000000e+000		
9	-8.189520e-023	5.998644e-027	0.000000e+000		
10	-5.874433e-023	6.722456e-027	0.000000e+000		
13	-4.318772e-026	1.626810e-030	0.000000e+000		
14	1.396749e-026	-1.796726e-030	0.000000e+000		
19	1.073164e-023	-1.635891e-027	0.000000e+000		
20	3.768240e-024	-1.287764e-027	0.000000e+000		
21	-6.771036e-027	9.395056e-032	0.000000e+000		
22	-6.969503e-027	-1.902148e-031	0.000000e+000		
25	6.340859e-028	-9.453066e-032	0.000000e+000		
26	-6.855560e-027	5.347354e-032	0.000000e+000		

[Numerical Example 11]

5						
		i	ri	di	ni	Obj-distance= 100.000
		1	649.023	13.500	1.50850	
		2	161.369	6.186		
		3	546.492	26.671	1.50850	
		4	-431.310	1.000		
		5	359.520	26.096	1.50850	
10		6	-820.769	1.000		
		7	225.399	26.602	1.50850	
		8	-8079.599	1.000		
		9	182.351	11.501	1.50850	
		10	106.062	34.137		
		11	-381.425	12.568	1.50850	
	ASP	12	-204.664	6.416		
15	ASP	13	-865.043	9.000	1.50850	
		14	160.026	38.823		
		15	-155.689	9.000	1.50850	
		16	171.836	25.571		
		17	-132.366	10.000	1.50850	
		18	285.824	45.894		
		19	-825.232	23.754	1.50850	
20		20	-232.487	1.000		
		21	2752.665	44.004	1.50850	
		22	-201.176	1.000		
		23	-17158.009	26.677	1.50850	
		24	-371.311	1.000		
		25	236.005	45.827	1.50850	
25		26	-936.533	1.000		
		27	409.539	20.925	1.50850	
	ASP	28	4743.410	43.481		
		29	-318.982	10.500	1.50850	
		30	159.949	37.876		
	ASP	31	-188.248	10.500	1.50850	
		32	275.952	58.220		
30		33	-417.384	30.810	1.50850	
		34	-279.212	2.737		
		35	1910.775	30.560	1.50850	
		36	-315.325	1.000		
		37	599.552	38.938	1.50850	
		38	-356.838	14.606		
		39	-226.768	23.000	1.50850	
35		40	-336.419	1.000		
		41	296.645	40.976	1.50850	
		42	-1194.936	1.000		
		43	231.667	27.972	1.50850	
		44	654.096	1.000		
		45	164.516	27.018	1.50850	
	ASP	46	281.664	55.351		
40		47	228.126	38.104	1.50850	
		48	601.950			

NA = 0.65
 $\beta = 1/5$
 L = 1100

aspherical surfaces

45		i	K	A	B	C	D
		12	0.000000e+000	2.721858e-008	4.440914e-012	-8.681662e-016	1.072700e-019
		13	0.000000e+000	2.261111e-008	5.977927e-012	-5.548672e-016	3.420032e-020
		29	0.000000e+000	5.769079e-009	2.101907e-012	-7.945428e-017	1.130602e-021
		32	0.000000e+000	3.262461e-009	-9.342932e-014	5.248637e-018	1.913566e-021
		47	0.000000e+000	-1.593367e-008	-4.300366e-012	-1.646850e-016	1.952807e-020
50		i	E	F	G		
		12	-1.000243e-023	5.037820e-028	0.000000e+000		
		13	-4.415014e-025	0.000000e+000	0.000000e+000		
		29	0.000000e+000	0.000000e+000	0.000000e+000		
		32	0.000000e+000	0.000000e+000	0.000000e+000		
		47	-6.144185e-026	0.000000e+000	0.000000e+000		

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[Numerical Example 12]

5		i	ri	di	ni	Obj-distance= 100.000
		1	762.804	16.049	1.56020	
		2	-469.191	0.100		
	ASP	3	201.770	24.476	1.56020	
		4	-641.970	0.100		
		5	119.260	11.000	1.56020	
		6	92.020	22.304		
10		7	502.773	11.000	1.56020	
	ASP	8	129.649	23.277		
	ASP	9	-196.636	11.000	1.56020	
		10	209.045	28.905		
		11	-167.151	13.779	1.56020	
		12	-219.660	0.100		
		13	-1321.329	26.454	1.56020	
15		14	-146.820	0.100		
		15	147.157	40.974	1.56020	
		16	-429.701	7.902		
		17	-772.858	12.082	1.56020	
		18	-329.657	6.785		
		19	-243.442	11.000	1.56020	
		20	186.253	28.938		
20		21	-194.264	11.000	1.56020	
		22	196.773	37.307		
		23	-134.218	12.871	1.56020	
		24	-1172.511	13.767		
		25	-298.586	22.347	1.56020	
		26	-179.413	0.100		
		27	-10481.480	43.039	1.56020	
25		28	-223.758	0.100		
		29	3482.244	42.189	1.56020	
		30	-296.976	0.100		
		31	204.855	60.135	1.56020	
		32	-2315.303	0.100		
	ASP	33	182.054	27.702	1.56020	
		34	359.872	10.166		
30		35	828.315	11.005	1.56020	
		36	146.178	44.572		
		37	-317.652	11.000	1.56020	
		38	142.088	40.682		
		39	-196.848	11.000	1.56020	
		40	610.693	8.809		
		41	2057.736	24.233	1.56020	
35		42	-278.801	0.100		
		43	606.192	33.247	1.56020	
		44	-282.084	50.656		
		45	333.953	30.963	1.56020	
		46	-1154.203	7.373		
		47	192.072	30.277	1.56020	
		48	709.117	2.142		
40		49	140.357	25.979	1.56020	
		50	271.887	49.191		
		51	246.870	36.087	1.56020	
	ASP	52	843.329			

NA = 0.65
 $\beta = 1/4$
L = 1130

aspherical surfaces

	i	K	A	B	C	D
45	3	0.000000e+000	-4.160344e-010	-8.173641e-013	-1.847702e-017	4.021619e-021
	8	0.000000e+000	-2.925267e-008	-4.791237e-012	-1.125265e-016	2.851327e-019
	9	0.000000e+000	-2.893504e-008	-2.541889e-013	-6.294070e-016	3.161482e-019
	33	0.000000e+000	-1.243289e-009	9.266574e-015	1.750090e-018	1.684224e-022
	52	0.000000e+000	7.000926e-008	1.194152e-011	6.581947e-017	-3.532015e-019
	i	E	F	G		
50	3	-2.340365e-025	0.000000e+000	0.000000e+000		
	8	-7.149298e-023	5.496942e-027	0.000000e+000		
	9	-7.755999e-023	6.724380e-027	0.000000e+000		
	33	-4.123949e-027	7.154662e-031	0.000000e+000		
	52	9.339549e-023	0.000000e+000	0.000000e+000		

[Numerical Example 13]

	i	ri	di	ni	Obj-distance= 110.304
5	1	566.177	17.071	1.56020	
	2	-537.616	0.100		
	3	297.012	18.535	1.56020	
	4	-1396.028	0.100		
	5	210.121	20.634	1.56020	
	6	-2473.292	0.100		
10	7	208.468	14.229	1.56020	
	8	102.590	22.179		
	9	-464.515	11.000	1.56020	
	10	158.021	17.175		
	11	-243.314	11.000	1.56020	
	12	266.770	15.357		
15	13	-215.829	23.557	1.56020	
	14	-165.735	0.187		
	15	-405.435	14.470	1.56020	
	16	-184.258	0.902		
	17	138.856	29.436	1.56020	
	18	-1241.175	0.169		
	19	814.292	12.155	1.56020	
20	20	171.534	30.877		
	21	-137.721	11.000	1.56020	
	22	204.947	33.998		
	23	-139.849	11.000	1.56020	
	24	-1002.418	13.925		
	25	-260.840	19.096	1.56020	
	26	-173.471	0.100		
25	27	-3848.952	39.207	1.56020	
	28	-218.919	0.100		
	29	1602.820	40.346	1.56020	
	30	-320.667	0.100		
	31	211.142	59.058	1.56020	
	32	-1777.340	1.773		
	33	206.544	28.127	1.56020	
30	34	468.888	14.670		
	35	759.016	11.000	1.56020	
	36	144.572	46.208		
	37	-241.701	11.286	1.56020	
	38	165.416	39.537		
	39	-186.712	11.000	1.56020	
	40	745.364	7.842		
35	41	-16420.189	26.080	1.56020	
	42	-241.902	0.100		
	43	652.031	33.185	1.56020	
	44	-318.590	47.429		
	45	354.585	38.707	1.56020	
	46	-930.788	7.713		
	47	222.294	32.201	1.56020	
40	48	1018.237	1.352		
	49	178.026	38.963	1.56020	
	50	1081.470	50.360		
	51	1050.015	55.018	1.56020	
	52	-734.877			

NA = 0.65

$\beta = 1/4$

L = 1130

aspherical surfaces

	K	A	B	C	D
19	0.000000e+000	5.037018e-009	1.095799e-012	-1.919844e-016	9.264552e-020
21	0.000000e+000	5.898908e-010	-3.300260e-013	3.428525e-016	-1.773740e-019
49	0.000000e+000	-1.190613e-008	-6.346279e-013	-2.514328e-017	-6.781741e-022

	E	F	G
19	-1.693773e-023	1.302335e-027	0.000000e+000
21	3.958228e-023	-3.245096e-027	0.000000e+000
49	-2.825622e-026	5.127567e-031	0.000000e+000

[Numerical Example 14]

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	i	ri	di	ni	Obj-distance= 90.862
	1	-370.530	21.483	1.56020	
	2	-142.320	0.700		
ASP	3	254.103	40.989	1.56020	
	4	-491.334	0.700		
	5	671.370	13.168	1.56020	
	6	120.679	17.806		
	7	-2878.732	11.000	1.56020	
ASP	8	207.692	19.442		
	9	-226.107	11.000	1.56020	
	10	598.193	36.591		
	11	1696.365	30.694	1.56020	
	12	-178.497	0.700		
ASP	13	512.692	34.956	1.56020	
	14	-214.839	0.700		
	15	100.024	44.492	1.56020	
	16	83.268	29.872		
	17	-685.024	11.000	1.56020	
	18	115.416	28.694		
	19	-106.310	11.000	1.56020	
	20	318.691	24.612		
	21	583.818	26.017	1.56020	
	22	-187.014	0.700		
	23	389.332	23.300	1.56020	
	24	-331.767	0.700		
	25	251.245	23.158	1.56020	
	26	-527.903	8.754		
	27	-253.401	11.000	1.56020	
	28	235.832	31.681		
	29	-131.657	11.000	1.56020	
	30	873.306	18.890		
	31	-516.228	44.528	1.50140	
	32	-194.523	21.344		
	33	1486.546	45.310	1.50140	
	34	-226.607	11.999		
	35	441.694	15.011	1.50140	
	36	-629.429	0.700		
	37	135.240	46.482	1.50140	
	38	450.927	0.700		
	39	120.725	28.158	1.56020	
	40	189.713	16.567		
	41	1257.096	31.621	1.56020	
	42	76.100	3.049		
ASP	43	80.000	47.000	1.56020	
	44	820.473			

NA = 0.65
 $\beta = 1/4$
 L = 1000

aspherical surfaces

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	I	K	A	B	C	D
	3	-9.872706e+000	6.624928e-008	-9.292370e-012	3.284321e-016	-3.612644e-020
	8	1.812763e+000	1.107600e-007	-1.441387e-011	-1.675187e-015	-4.421521e-020
	13	-4.067550e+000	1.555416e-008	-7.163014e-013	-1.829797e-017	1.589327e-022
	43	1.776067e-002	-6.163923e-008	-6.499724e-012	-8.076654e-016	8.476241e-020

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	I	E	F	G
	3	5.160574e-024	-2.667799e-028	0.000000e+000
	8	4.516444e-023	-3.633179e-027	0.000000e+000
	13	8.977418e-026	-3.648511e-030	0.000000e+000
	43	-3.474625e-023	4.982009e-027	0.000000e+000

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[Numerical Example 15]

5		i	ri	di	ni	Obj-distance= 64.400	
	ASP	1	∞	21.483	1.56020		
		2	-223.520	0.700			
		3	324.053	19.299	1.56020		
		4	-353.700	42.878			
		5	-194.376	11.000	1.56020		
10		6	169.712	9.737			
		7	∞	11.000	1.56020		
	ASP	8	176.122	49.836			
		9	∞	22.771	1.56020		
	ASP	10	-185.168	0.700			
		11	423.634	23.637	1.56020		
		12	-244.092	34.286			
15		13	-219.694	11.000	1.56020		
		14	180.011	35.532			
	ASP	15	-101.095	11.000	1.56020		
		16	∞	36.544			
		17	∞	41.224	1.56020		
	ASP	18	-165.000	0.700			
		19	613.013	37.099	1.56020		
20		20	-314.622	0.700			
		21	155.889	46.421	1.56020		
		22	-16193.780	37.763			
		23	-545.453	11.000	1.56020		
		24	123.496	47.345			
	ASP	25	-107.334	11.000	1.56020		
25		26	∞	22.957			
		27	∞	39.601	1.56020		
		28	-369.755	32.400			
		29	∞	31.385	1.56020		
	ASP	30	-260.069	3.099			
		31	320.054	36.813	1.56020		
		32	-1109.205	0.700			
30		33	180.000	44.852	1.56020		
		34	∞	0.700			
		35	118.000	45.269	1.56020		
		36	243.132	13.160			
		37	-1170.643	16.269	1.56020		
		38	83.151	5.965			
35	ASP	39	113.618	41.305	1.56020		
		40	∞				
					NA=0.65		
					β = 1/4		
					L = 1000		
	aspherical surfaces						
40		I	K	A	B	C	D
		2	0.000000e+000	-2.461170e-008	-1.254678e-012	1.741418e-017	-3.942618e-021
		8	0.000000e+000	1.330433e-008	3.996524e-012	-6.425340e-016	8.519215e-020
		10	0.000000e+000	-7.314349e-008	-3.668407e-013	-6.551240e-017	-5.612962e-021
		15	0.000000e+000	-8.288231e-008	4.470040e-012	9.953928e-016	1.175441e-019
		18	0.000000e+000	-3.010817e-009	7.230562e-013	1.976312e-017	3.752192e-022
		25	0.000000e+000	-2.381635e-008	5.863091e-013	1.887350e-017	-6.092378e-021
		30	0.000000e+000	1.189738e-009	2.579270e-013	-9.540845e-019	1.898098e-022
45		39	0.000000e+000	-5.338672e-008	2.479306e-011	2.425502e-015	-1.556929e-019
		I	E	F	G		
		2	2.970299e-027	0.000000e+000	0.000000e+000		
		8	-1.018743e-023	0.000000e+000	0.000000e+000		
		10	-1.001277e-024	0.000000e+000	0.000000e+000		
		15	4.568658e-025	0.000000e+000	0.000000e+000		
50		18	-2.789718e-026	0.000000e+000	0.000000e+000		
		25	2.398328e-024	0.000000e+000	0.000000e+000		
		30	-4.477469e-027	0.000000e+000	0.000000e+000		
		39	7.470691e-023	0.000000e+000	0.000000e+000		

[Numerical Example 16]

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	i	ri	di	ni	Obj-distance= 70.000
ASP	1	426.303	22.143	1.56020	
ASP	2	-293.270	44.991		
ASP	3	-239.063	12.287	1.56020	
ASP	4	193.554	56.615		
	5	8175.282	27.396	1.56020	
	6	-172.317	0.700		
	7	485.638	29.517	1.56020	
	8	-226.633	62.198		
ASP	9	-543.539	11.000	1.56020	
ASP	10	98.865	29.468		
	11	-166.560	11.000	1.56020	
	12	579.649	35.061		
	13	804.055	34.406	1.56020	
	14	-152.871	0.700		
	15	163.018	31.782	1.56020	
	16	-1638.880	46.140		
	17	-383.725	11.000	1.56020	
	18	161.783	30.642		
	19	-147.895	15.264	1.56020	
	20	335.023	21.043		
	21	-1046.740	35.362	1.56020	
	22	-250.766	9.458		
	23	720.726	25.727	1.56020	
	24	-397.727	94.567		
	25	980.555	34.089	1.56020	
	26	-357.146	0.700		
	27	133.000	50.773	1.56020	
	28	386.552	0.918		
	29	107.997	41.164	1.56020	
	30	169.965	13.455		
	31	539.514	19.429	1.56020	
	32	106.461	0.700		
ASP	33	92.023	41.003	1.56020	
ASP	34	110.938			

NA=0.65
 $\beta = 1/4$
 L = 1000

aspherical surfaces

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i	K	A	B	C	D
1	0.000000e+000	1.179390e-007	-2.481342e-012	-8.514994e-016	-5.507741e-021
2	0.000000e+000	1.984808e-009	-2.379609e-012	-1.277691e-015	2.269844e-019
3	0.000000e+000	-6.127062e-008	-2.439639e-011	4.940348e-015	1.783844e-019
4	0.000000e+000	1.351928e-007	-2.155565e-011	4.979933e-015	-2.254154e-020
9	0.000000e+000	-1.029855e-008	4.222175e-013	9.252409e-016	-1.320195e-020
10	0.000000e+000	-1.647436e-008	-6.863313e-012	2.498019e-016	3.078894e-021
33	0.000000e+000	-7.872670e-008	3.170754e-012	7.552635e-016	1.265430e-018
34	0.000000e+000	5.393494e-007	1.483362e-010	4.549512e-014	5.826949e-017

i	E	F	G
1	4.244235e-023	1.894592e-027	0.000000e+000
2	2.746013e-023	6.870822e-028	0.000000e+000
3	-3.758891e-023	-1.387715e-026	0.000000e+000
4	-1.550011e-022	1.237198e-026	0.000000e+000
9	-2.287173e-023	1.356755e-027	0.000000e+000
10	-4.351537e-023	6.281604e-028	0.000000e+000
33	-3.541330e-022	7.175403e-026	0.000000e+000
34	-4.706812e-020	3.185353e-023	0.000000e+000

[Numerical Example 17]

		rl	di	nl	Obj-distance=	90. 538
5		1	17. 000	1. 603377		
	ASP	2	415. 839	49. 200		
		3	-10081. 321	26. 766	1. 594224	
		4	-328. 287	10. 248		
		5	1129. 412	28. 656	1. 594224	
10		6	-308. 478	2. 981		
		7	347. 593	20. 835	1. 594224	
		8	30560. 909	9. 470		
		9	192. 586	28. 028	1. 594224	
		10	600. 221	21. 523	1. 603377	
		11	113. 162	42. 174		
	ASP	12	-1287. 217	17. 646	1. 603377	
15		13	201. 828	24. 429		
		14	-230. 109	18. 460	1. 594224	
		15	129. 305	38. 186	1. 603377	
		16	-310. 734	7. 182		
		17	302. 807	25. 115	1. 480884	
		18	-190. 854	4. 421		
		19	340. 589	19. 913	1. 480884	
20		20	-219. 421	3. 874		
		21	-181. 985	15. 000	1. 603377	
		22	160. 986	81. 067		
		23	-141. 832	16. 077	1. 603377	
		24	-271. 520	12. 534		
		25	892. 494	23. 757	1. 480884	
		26	-165. 761	16. 728		
25	ASP	27	641. 696	18. 838	1. 480884	
		28	-315. 023	0. 152		
		29	287. 866	21. 464	1. 480884	
		30	4039. 331	3. 404		
		31	191. 617	37. 590	1. 603377	
		32	-258. 209	22. 761	1. 594224	
		33	130. 065	41. 379		
30	ASP	34	-429. 130	12. 144	1. 603377	
		35	941. 156	61. 542		
		36	-105. 300	24. 184	1. 603377	
		37	-3332. 376	27. 927	1. 594224	
		38	-183. 797	14. 302		
		39	-113. 095	33. 829	1. 603377	
		40	-6034. 000	0. 100		
35		41	4882. 455	41. 773	1. 594224	
		42	-231. 974	0. 100		
		43	784. 515	28. 037	1. 594224	
		44	-400. 896	0. 100		
		45	259. 744	24. 506	1. 594224	
		46	1013. 135	48. 052		
	ASP	47	-991. 262	20. 000	1. 603377	
40		48	-5753. 507			

NA = 0. 1
 β = 1. 25
L = 1250

aspherical surfaces

		K	A	B	C	D
45	2	0.000000e+000	1.732651e-010	8.978816e-014	6.675870e-019	2.108700e-023
	13	0.000000e+000	3.987781e-008	6.862497e-013	-3.270813e-017	-1.827952e-020
	27	0.000000e+000	-1.383583e-008	-4.200967e-013	-4.907918e-018	-1.233173e-023
	34	0.000000e+000	6.892230e-008	5.467352e-012	1.616376e-016	2.002978e-020
	47	0.000000e+000	-7.437008e-009	7.059486e-014	1.729433e-018	-6.315660e-023
50	i		E	F	G	
	2	0.000000e+000	0.000000e+000	0.000000e+000		
	13	0.000000e+000	0.000000e+000	0.000000e+000		
	27	0.000000e+000	0.000000e+000	0.000000e+000		
	34	0.000000e+000	0.000000e+000	0.000000e+000		
	47	0.000000e+000	0.000000e+000	0.000000e+000		

[Numerical Example 18]

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	i	ri	di	ni	Obj-distance= 74.305
	1	373.120	12.974	1.56020	
10	ASP 2	164.628	47.146		
	3	-3359.229	32.768	1.56020	
	4	-218.105	86.869		
	ASP 5	2738.452	28.445	1.56020	
	6	-304.496	3.530		
	7	118.714	38.886	1.56020	
15	8	395.116	54.147		
	9	-185.784	14.201	1.56020	
	ASP 10	155.206	27.288		
	11	-141.565	12.480	1.56020	
	ASP 12	114.106	26.423		
	13	-204.014	18.463	1.56020	
20	14	-353.327	71.915		
	15	-2046.298	46.133	1.56020	
	16	-200.916	1.000		
	17	890.257	38.648	1.56020	
	18	-337.058	124.746		
25	ASP 19	444.270	35.791	1.56020	
	20	-539.937	1.293		
	21	156.861	56.316	1.56020	
	22	493.741	60.723		
	23	162.767	17.902	1.56020	
	24	87.061	4.114		
30	25	74.355	33.695	1.56020	
	26	171.271			

aspherical surfaces

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	i	K	A	B	C	D
	2	0.000000e+000	-6.151422e-008	2.635679e-012	-4.629311e-017	1.256802e-022
	5	4.022519e+002	3.238513e-008	1.444575e-012	-1.299191e-017	-2.782533e-021
	10	0.000000e+000	9.060021e-008	6.368879e-011	1.867166e-015	9.142776e-020
40	12	0.000000e+000	2.327945e-007	-8.622504e-011	7.848182e-017	1.872815e-018
	19	0.000000e+000	-1.195187e-008	-1.416116e-013	-6.278820e-019	-4.370204e-024
	i	E	F	G		
	2	-5.255483e-025	8.024017e-029	0.000000e+000		
	5	1.258182e-026	1.216906e-030	0.000000e+000		
	10	8.772362e-023	-1.631989e-026	0.000000e+000		
45	12	-2.673162e-022	9.539079e-027	0.000000e+000		
	19	-8.269803e-028	-1.146333e-032	0.000000e+000		

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$$\begin{aligned}
 NA &= 0.65 \\
 \beta &= 1/4 \\
 L &= 1000
 \end{aligned}$$

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[Numerical Example 19]

	i	rl	dl	ni	Obj-distance= 159.910
ASP	1	1426.235	13.395	1.56020	
ASP	2	-18546.845	1.000		
	3	234.396	26.952	1.56020	
	4	-1043.490	1.000		
	5	132.015	29.134	1.56020	
	6	695.945	36.199		
	7	-2151.684	8.000	1.56020	
ASP	8	119.308	40.946		
ASP	9	0.000	10.001	1.56020	
ASP	10	139.306	32.296		
	11	-64.778	7.500	1.56020	
	12	358.861	59.331		
	13	1808.193	41.533	1.56020	
	14	-190.795	1.000		
	15	-12637.113	27.113	1.56020	
ASP	16	-309.272	2.989		
	17	329.502	39.999	1.56020	
	18	361.110	99.711		
	19	422.259	46.890	1.56020	
	20	-1020.802	95.132		
ASP	21	213.405	42.491	1.56020	
	22	22708.670	1.000		
	23	152.762	43.718	1.56020	
	24	713.753	23.810		
	25	-1740.329	10.000	1.56020	
	26	272.427	1.000		
ASP	27	214.892	31.772	1.56020	
	28	1651.406			

aspherical surfaces

i	K	A	B	C	D
1	0.000000e+000	5.655433e-009	-9.761116e-013	-5.760406e-017	-8.900881e-021
2	0.000000e+000	-6.971343e-008	1.596973e-012	-1.156489e-016	-6.146567e-021
8	2.062997e+000	3.046348e-007	-2.473855e-011	-1.369273e-015	-2.096578e-018
9	0.000000e+000	-1.273407e-007	-5.392020e-011	2.383841e-014	-4.688497e-018
10	-5.185475e+000	-1.153426e-007	-6.068909e-011	2.958140e-014	-4.936248e-018
16	1.483773e-001	1.529142e-008	2.653064e-013	-1.610087e-018	1.839705e-022
21	5.505534e-002	-1.395115e-008	-3.478119e-013	-8.176869e-018	7.786648e-023
27	0.000000e+000	-2.915211e-008	4.096900e-012	1.642705e-016	-1.898429e-020

i	E	F	G
1	6.018890e-025	1.226600e-028	-4.790467e-033
2	3.857142e-025	1.130926e-028	-3.918967e-033
8	5.848018e-022	-2.847819e-025	-6.295862e-031
9	-1.461126e-022	-1.331753e-025	9.443424e-030
10	-1.811705e-022	-9.260870e-026	5.901073e-029
16	-2.145983e-026	1.090597e-030	-2.080577e-035
21	-1.742447e-026	6.151744e-031	-1.381606e-035
27	-9.051554e-026	1.744600e-028	-1.046852e-032

$$NA = 0.65$$

$$\beta = 1/4$$

$$L = 1000$$

[Numerical Example 20]

Object to First Surface Distance: 98.214 mm

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i	ri	di	ni
1	0.000	26.026	1.56020
2	-182.658	1.000	
3	-2698.945	14.661	1.56020
4	-306.331	1.000	
5	274.751	13.789	1.56020
6	949.145	1.000	
7	273.833	11.000	1.56020
8	140.490	17.638	
9	-582.890	11.000	1.56020
10	207.947	18.628	
11	-226.022	11.000	1.56020
12	235.468	73.861	
13	826.269	32.989	1.56020
14	-232.749	1.000	
15	480.682	30.232	1.56020
16	-377.116	1.000	
17	350.466	27.974	1.56020
18	-547.948	58.535	
19	-577.129	11.000	1.56020
20	159.547	20.289	
21	-210.322	11.000	1.56020
22	127.412	106.550	
23	0.0(stop)	28.400	
24	1512.402	26.036	1.56020
25	-336.438	4.111	
26	291.888	38.182	1.56020
27	-1333.617	109.565	
28	243.299	38.039	1.56020
29	-1496.216	1.000	
30	160.404	31.231	1.56020
31	423.056	1.000	
32	120.000	40.969	1.56020
33	122.677	3.894	
34	137.160	39.075	1.56020
35	94.932		

aspherical surfaces

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i	K	A	B	C	D
5	0.000000e+000	3.967358e-008	-3.864245e-012	3.966438e-017	-3.558419e-020
10	0.000000e+000	1.997893e-007	-1.002364e-011	-7.614655e-016	-1.609150e-019
15	0.000000e+000	3.455575e-009	-7.722473e-013	1.315998e-017	-2.730036e-022
22	0.000000e+000	-1.853322e-008	-9.221953e-012	1.109905e-016	3.582375e-020
25	0.000000e+000	1.081702e-008	2.252523e-013	4.022520e-018	3.297878e-023
28	0.000000e+000	-6.543627e-009	-4.416705e-013	-4.129965e-018	-1.173134e-022
35	0.000000e+000	2.039958e-007	1.023185e-012	-2.445114e-015	-2.255754e-018

i	E	F	G
5	7.378869e-024	-5.305032e-028	0.000000e+000
10	5.840329e-023	-5.965041e-027	0.000000e+000
15	1.226431e-026	-5.374728e-031	0.000000e+000
22	-5.440508e-024	1.859686e-028	0.000000e+000
25	-4.516028e-028	1.861970e-032	0.000000e+000
28	2.636446e-027	-2.053727e-031	0.000000e+000
35	3.096130e-022	-1.399174e-025	0.000000e+000

[Numerical Example 21]

Object to First Surface Distance: 98.335 mm

i	ri	di	ni
1	287.464	31.801	1.56020
2	-221.023	1.981	
3	178.289	23.482	1.56020
4	100.774	16.799	
5	185.474	28.268	1.56020
6	-248.716	12.641	
7	-1830.438	15.601	1.56020
8	118.144	13.340	
9	-672.129	12.203	1.56020
10	128.731	22.260	
11	-128.312	12.613	1.56020
12	260.849	61.688	
13	1090.602	36.650	1.50140
14	-263.371	3.385	
15	1451.653	34.659	1.50140
16	-321.128	1.422	
17	500.707	28.672	1.50140
18	-961.818	1.000	
19	198.015	57.083	1.50140
20	-507.319	51.127	
21	-267.052	14.311	1.56020
22	232.559	30.137	
23	-158.226	11.000	1.56020
24	221.812	17.262	
25	0.0(stop)	19.227	
26	-714.808	23.000	1.50140
27	-191.620	38.957	
28	2124.929	40.223	1.50140
29	-254.397	1.000	
30	2531.830	22.743	1.50140
31	-476.179	1.000	
32	141.233	50.770	1.50140
33	550.246	3.129	
34	117.089	43.874	1.50140
35	271.650	6.116	
36	392.644	18.787	1.56020
37	83.993	6.558	
38	86.609	47.000	1.56020
39	316.957		

aspherical surfaces

i	K	A	B	C	D
2	4.160031e-001	2.884143e-008	6.582259e-013	-7.423743e-017	1.346767e-020
10	-1.359457e+000	1.735654e-007	1.154047e-012	-1.526172e-015	1.015673e-018
11	-2.480087e-001	4.977349e-008	3.201767e-012	1.930247e-016	1.184675e-018
17	5.040159e-001	8.569390e-010	2.159964e-014	-1.113895e-017	-2.193301e-022
23	1.984249e-001	-2.580296e-008	5.027557e-012	2.016255e-016	3.503224e-020
27	-2.942081e-002	1.540566e-010	6.050464e-013	-9.832385e-018	5.668874e-021
30	1.078454e+001	-8.926844e-011	-1.049507e-014	-7.767053e-018	3.904718e-022
38	-1.504836e-001	-6.739257e-009	-8.785331e-012	-1.376541e-015	-6.840122e-019

i	E	F	G
2	-1.692505e-024	7.844268e-029	0.000000e+000
10	-5.010171e-022	4.485536e-026	0.000000e+000
11	-2.420938e-022	2.859077e-026	0.000000e+000
17	7.842541e-027	-4.643321e-031	0.000000e+000
23	-5.218697e-024	2.670135e-028	0.000000e+000
27	-5.021468e-025	2.055561e-029	0.000000e+000
30	-2.840378e-026	6.584930e-031	0.000000e+000
38	7.189611e-023	-2.842751e-026	0.000000e+000

[Numerical Example 22]

Object to First Surface Distance: 98.214 mm

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i	ri	di	ni
1	0.000	35.283	1.56020
2	-202.253	1.000	
3	196.472	21.687	1.56020
4	0.000	1.000	
5	163.840	20.913	1.56020
6	108.642	18.007	
7	0.000	11.000	1.56020
8	142.097	21.663	
9	-196.412	11.000	1.56020
10	211.337	68.733	
11	0.000	26.767	1.56020
12	-223.854	1.000	
13	693.208	33.377	1.56020
14	-259.524	1.000	
15	349.600	29.343	1.56020
16	-488.748	59.416	
17	0.000	11.000	1.56020
18	177.628	22.570	
19	-171.815	11.000	1.56020
20	148.088	96.964	
21	0.0(stop)	31.152	
22	0.000	25.233	1.56020
23	-283.913	8.408	
24	274.841	38.513	1.56020
25	-1832.307	100.711	
26	239.348	33.960	1.56020
27	0.000	1.033	
28	169.199	32.449	1.56020
29	540.334	1.000	
30	120.352	44.300	1.56020
31	86.480	3.768	
32	93.410	41.306	1.56020
33	100.526		

aspherical surfaces

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i	K	A	B	C	D
3	0.000000e+000	3.650790e-008	-9.230325e-013	5.957551e-017	-2.805723e-020
8	0.000000e+000	1.769184e-007	1.795818e-012	-3.786678e-016	-3.120635e-019
12	0.000000e+000	-1.662398e-009	1.085256e-013	-3.042158e-018	7.706400e-022
18	0.000000e+000	-1.731542e-008	-4.620024e-012	-2.904976e-016	-2.146101e-020
23	0.000000e+000	9.562980e-009	1.835166e-013	4.699629e-018	1.232888e-022
26	0.000000e+000	-5.523449e-009	-4.344737e-013	-4.397292e-018	-1.896027e-022
33	0.000000e+000	2.159918e-007	1.616246e-011	8.393394e-016	-2.980107e-018

i	E	F	G
3	4.592119e-024	-2.738347e-028	0.000000e+000
8	7.179478e-023	-7.666732e-027	0.000000e+000
12	-3.545587e-026	3.177747e-030	0.000000e+000
18	-1.843132e-025	-3.621190e-028	0.000000e+000
23	-1.671856e-027	1.331041e-031	0.000000e+000
26	1.392972e-027	-2.305348e-031	0.000000e+000
33	7.162464e-022	-2.675240e-025	0.000000e+000

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[Numerical Example 23]

Object to First Surface Distance: 106.385 mm

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i	ri	di	ni
1	0.000	18.041	1.56020
2	-247.429	1.000	
3	219.985	22.003	1.56020
4	0.000	68.685	
5	0.000	10.923	1.56020
6	120.000	27.648	
7	-108.637	10.923	1.56020
8	214.504	71.415	
9	0.000	35.572	1.56020
10	-224.080	1.000	
11	1433.942	38.955	1.56020
12	-280.000	1.000	
13	519.014	35.927	1.56020
14	-450.000	1.000	
15	138.532	33.304	1.56020
16	294.893	39.798	
17	∞	10.923	1.56020
18	105.077	38.260	
19	-170.288	10.923	1.56020
20	148.736	65.400	
21	0.0(stop)	23.213	
22	0.000	29.628	1.56020
23	-237.930	1.000	
24	313.490	47.271	1.56020
25	-503.041	64.620	
26	287.758	27.098	1.56020
27	0.000	4.702	
28	269.078	38.857	1.56020
29	-669.791	1.000	
30	129.185	33.484	1.56020
31	155.969		

aspherical surfaces

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i	K	A	B	C	D
3	0.000000e+000	2.528207e-008	4.962350e-013	3.071542e-017	3.550497e-021
6	0.000000e+000	-2.819139e-008	-9.031712e-012	-5.509380e-016	-4.368963e-019
8	-6.736209e-001	3.050101e-008	4.262540e-012	-8.456760e-017	-9.973877e-021
10	0.000000e+000	-5.618244e-009	1.626901e-013	-7.890662e-018	-8.409742e-023
18	0.000000e+000	2.731662e-008	-4.745926e-012	-4.360318e-016	2.047793e-020
23	0.000000e+000	1.506776e-008	2.875274e-014	9.782798e-018	-1.279117e-022
26	0.000000e+000	-9.390134e-009	-1.137122e-012	1.260621e-017	-8.405644e-022

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i	E	F	G
3	-1.267417e-024	2.105416e-028	-9.135087e-033
6	1.610697e-022	-6.691954e-026	1.018697e-029
8	2.488445e-023	-6.291342e-027	2.742974e-031
10	5.405900e-027	-1.183796e-030	9.723656e-035
18	-2.603323e-023	4.124923e-027	-4.240206e-031
23	1.352392e-026	-5.887927e-031	-1.075106e-035
26	3.517040e-026	-1.261846e-030	1.403193e-035

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[Numerical Example 24]

5 Object to First Surface Distance: 70 mm

i	rl	dl	nl
1	208.834	40.000	1.56020
2	-2204.367	48.301	
3	117.104	40.000	1.56020
4	136.645	23.945	
5	-141.268	10.000	1.56020
6	153.903	29.127	
7	-86.471	22.693	1.56020
8	-2380.713	74.228	
9	13162.964	54.046	1.56020
10	-197.958	1.000	
11	1153.120	50.098	1.56020
12	-272.743	1.000	
13	164.261	55.052	1.56020
14	695.660	65.937	
15	-792.673	18.178	1.56020
16	163.351	43.522	
17	-154.770	10.000	1.56020
18	466.852	25.418	
19	0.0(stop)	44.864	
20	1313.769	39.444	1.56020
21	-230.952	1.401	
22	230.618	41.629	1.56020
23	-1095.767	4.457	
24	162.697	36.856	1.56020
25	521.931	56.084	
26	126.480	36.438	1.56020
27	394.895		

35 aspherical surfaces

i	K	A	B	C	D
1	-3.466662e-001	1.433507e-007	-2.133046e-012	5.836183e-017	0.000000e+000
2	2.000000e+000	7.959536e-008	-3.744217e-012	-1.133348e-016	0.000000e+000
3	1.004511e+000	-1.573887e-007	-6.456960e-012	8.518749e-016	0.000000e+000
4	-6.754456e-001	-1.134021e-007	2.106544e-011	-3.105587e-016	0.000000e+000
5	1.323098e+000	-1.227290e-008	1.434144e-013	-4.525546e-018	0.000000e+000
6	1.664589e-001	-1.227018e-009	1.626884e-013	-1.920513e-018	0.000000e+000
7	-2.000000e+000	-5.085760e-008	4.139140e-012	-8.157887e-017	0.000000e+000
8	9.336532e-001	-2.144321e-008	-9.878780e-014	-1.742585e-017	0.000000e+000
9	-3.149396e-001	-2.740779e-009	-2.124860e-013	5.859505e-018	0.000000e+000
10	-4.067584e-001	9.667551e-009	2.056572e-014	4.774158e-018	0.000000e+000
11	-2.127815e-001	-5.135833e-008	-3.003067e-012	-5.838412e-018	0.000000e+000
12	1.283433e-001	-8.510284e-008	6.429230e-012	-1.847620e-016	0.000000e+000

[Numerical Example 25]

	i	ri	di	ni	Obj-distance= 64.400
	1	0.000	21.483	1.56020	
	2	-234.177	32.837		
	3	-217.725	11.000	1.56020	
10	4	417.996	33.850		
	5	0.000	22.468	1.56020	
	6	-187.357	0.700		
	7	146.365	26.864	1.56020	
	8	2044.065	74.989		
	9	-217.939	11.000	1.56020	
15	10	218.942	19.185		
	11	-111.200	11.000	1.56020	
	12	162.388	83.304		
	13	4095.070	42.510	1.56020	
	14	-165.000	0.700		
	15	201.723	45.798	1.56020	
20	16	-760.044	82.340		
	17	-183.459	11.000	1.56020	
	18	188.694	20.034		
	19	0.0(stop)	68.080		
	20	-2875.458	19.965	1.56020	
	21	-387.830	0.700		
25	22	366.325	37.399	1.56020	
	23	-613.820	45.002		
	24	243.386	40.478	1.56020	
	25	-4311.737	0.700		
	26	181.915	35.797	1.56020	
	27	981.126	0.700		
30	28	119.183	27.705	1.56020	
	29	256.810	9.045		
	30	770.652	11.000	1.56020	
	31	80.000	10.112		
	32	122.097	47.000	1.56020	
	33	275.295			

aspherical surfaces

	i	K	A	B	C	D
40	2	0.000000e+000	-1.114212e-007	1.060175e-011	-7.279118e-016	4.276504e-020
	3	0.000000e+000	-7.330288e-008	1.877977e-011	-1.654304e-015	1.154005e-019
	7	0.000000e+000	1.794366e-008	-1.746620e-012	2.819556e-016	-1.250857e-020
	11	0.000000e+000	-1.072701e-007	-1.342596e-012	7.030022e-016	5.449568e-020
	17	0.000000e+000	-1.232061e-008	1.881693e-012	2.948112e-017	-2.584618e-021
	23	0.000000e+000	5.143208e-009	1.895658e-013	-2.954221e-018	5.204719e-023
	32	0.000000e+000	2.598613e-008	5.141410e-012	-1.743487e-016	4.963194e-020
45						
50	i	E	F	G		
	2	-7.962637e-025	0.000000e+000	0.000000e+000		
	3	-1.636200e-024	0.000000e+000	0.000000e+000		
	7	4.866995e-025	0.000000e+000	0.000000e+000		
	11	5.143056e-023	0.000000e+000	0.000000e+000		
	17	1.229520e-026	0.000000e+000	0.000000e+000		
	23	-5.427645e-028	0.000000e+000	0.000000e+000		
	32	-1.947370e-023	0.000000e+000	0.000000e+000		

[Numerical Example 26]

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i	ri	di	ni	Obj-distance= 64.400
1	0.000	21.483	1.56020	
2	-271.019	30.857		
3	-186.431	11.000	1.56020	
4	377.095	90.975		
5	0.000	35.430	1.56020	
6	-185.000	0.700		
7	151.070	39.238	1.56020	
8	1525.179	108.989		
9	-184.857	11.000	1.56020	
10	158.888	22.082		
11	-115.966	11.000	1.56020	
12	200.996	49.352		
13	1443.076	22.804	1.56020	
14	-240.000	0.700		
15	592.928	23.665	1.56020	
16	-355.050	0.700		
17	625.018	20.144	1.56020	
18	-499.230	50.000		
19	-250.000	11.000	1.56020	
20	277.792	12.891		
21	0.0(ztop)	82.481		
22	-1590.684	20.499	1.56020	
23	-351.242	0.700		
24	404.653	33.976	1.56020	
25	-683.152	9.822		
26	209.688	43.949	1.56020	
27	6079.638	0.700		
28	180.000	34.764	1.56020	
29	822.298	0.700		
30	126.160	36.259	1.56020	
31	255.231	7.763		
32	787.363	11.000	1.56020	
33	80.000	25.213		
34	105.503	32.765	1.56020	
35	223.176			

aspherical surfaces

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i	K	A	B	C	D
2	0.000000e+000	-1.827721e-007	8.436255e-012	-1.730566e-016	-2.453104e-020
3	0.000000e+000	-1.541073e-007	9.297673e-012	1.092750e-016	-6.194075e-020
7	0.000000e+000	-3.457815e-009	-4.045005e-013	8.652080e-019	1.619763e-022
11	0.000000e+000	-3.488911e-008	2.531397e-012	4.332109e-016	5.967441e-022
15	0.000000e+000	-1.645970e-008	8.280400e-013	2.969915e-017	-8.774617e-022
25	0.000000e+000	5.665653e-009	1.466511e-013	2.030552e-019	7.156711e-025
34	0.000000e+000	-1.182366e-008	-8.975848e-012	-2.065253e-015	-1.730388e-019

i	E	F	G
2	2.289130e-024	0.000000e+000	0.000000e+000
3	1.780862e-024	0.000000e+000	0.000000e+000
7	-2.365878e-026	0.000000e+000	0.000000e+000
11	3.321880e-024	0.000000e+000	0.000000e+000
15	-1.320677e-026	0.000000e+000	0.000000e+000
25	6.628893e-028	0.000000e+000	0.000000e+000
34	-1.610493e-022	0.000000e+000	0.000000e+000

[Numerical Example 27]

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i	r _i	d _i	n _i	Obj-distance= 59.534
1	0.000	16.600	1.56020	
2	-202.380	0.800		
3	280.147	18.709	1.56020	
4	-445.924	22.855		
5	0.000	18.941	1.56020	
6	107.558	15.137		
7	0.000	11.000	1.56020	
8	106.669	39.484		
9	0.000	22.061	1.56020	
10	-180.483	0.800		
11	187.380	24.573	1.56020	
12	-623.254	10.000		
13	140.566	23.864	1.56020	
14	107.526	29.179		
15	-151.872	11.000	1.56020	
16	171.516	30.143		
17	-112.343	11.000	1.56020	
18	0.000	30.281		
19	-435.825	46.381	1.56020	
20	-127.000	0.800		
21	325.622	46.741	1.56020	
22	-410.690	0.800		
23	187.578	45.209	1.56020	
24	0.000	46.773		
25	-482.585	11.000	1.56020	
26	157.836	41.196		
27	-175.762	11.000	1.56020	
28	253.867	16.534		
29	0.0(stop)	31.669		
30	0.000	40.310	1.56020	
31	-213.855	1.457		
32	794.896	33.225	1.56020	
33	-385.054	0.800		
34	308.035	38.589	1.56020	
35	-847.571	0.800		
36	145.851	47.000	1.56020	
37	284.015	70.097		
38	232.327	44.283	1.56020	
39	0.000			

aspherical surfaces

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i	K	A	B	C	D
2	0.000000e+000	3.441391e-008	-2.616189e-012	3.176226e-017	-2.861419e-020
6	0.000000e+000	-7.554035e-008	-8.113440e-012	4.320580e-015	6.099900e-019
8	0.000000e+000	-1.174998e-007	1.010874e-011	-6.601546e-015	-5.325149e-019
10	0.000000e+000	-7.107743e-008	-5.995307e-012	-3.259545e-016	3.029660e-021
17	0.000000e+000	-6.901972e-008	-6.690174e-012	-3.236268e-016	7.966691e-020
23	0.000000e+000	3.462617e-010	2.376572e-013	1.798095e-018	4.781755e-022
31	0.000000e+000	1.055515e-009	-3.653336e-014	-1.317019e-018	7.398814e-023
38	0.000000e+000	7.064793e-009	-9.877785e-012	-4.240566e-017	-3.792715e-020

i	E	F	G
2	8.104470e-024	-7.296145e-028	0.000000e+000
6	-1.472017e-022	2.367379e-026	0.000000e+000
8	1.095341e-022	-7.413466e-027	0.000000e+000
10	-4.964934e-024	2.870385e-028	0.000000e+000
17	-2.373952e-023	5.464713e-027	0.000000e+000
23	-1.877652e-026	1.189180e-030	0.000000e+000
31	-1.025990e-026	6.116071e-031	0.000000e+000
38	-1.452718e-024	1.117639e-027	0.000000e+000

[Numerical Example 28]

5	i	ri	di	ni	Obj-distance= 65.000
	1	-103485.230	17.433	1.56020	
	2	-201.292	0.800		
	3	370.683	17.976	1.56020	
10	4	-407.200	30.000		
	5	-456.784	11.000	1.56020	
	6	145.860	16.510		
	7	-503.955	11.000	1.56020	
	8	203.717	34.000		
	9	-424.708	21.358	1.56020	
	10	-129.351	0.800		
15	11	801.838	28.215	1.56020	
	12	-175.733	20.000		
	13	159.132	11.676	1.56020	
	14	100.036	23.873		
	15	-515.415	11.000	1.56020	
	16	178.045	27.455		
	17	-115.893	11.000	1.56020	
20	18	541.607	40.357		
	19	-1434.439	37.615	1.56020	
	20	-151.851	0.800		
	21	358.551	36.516	1.56020	
	22	-463.136	0.800		
	23	165.301	40.791	1.56020	
	24	1423.496	53.809		
25	25	-2299.149	11.000	1.56020	
	26	121.688	38.458		
	27	-170.387	11.000	1.56020	
	28	283.691	11.212		
	29	0.0(stop)	32.285		
	30	772.565	47.000	1.56020	
	31	-258.987	35.308		
30	32	377.097	34.035	1.56020	
	33	-636.486	0.800		
	34	184.387	37.630	1.56020	
	35	702.528	5.509		
	36	150.000	44.788	1.56020	
	37	253.503	29.946		
	38	99.159	47.000	1.56020	
35	39	110.423			

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	i	K	A	B	C	D
40	3	0.000000e+000	2.751774e-008	-1.770975e-012	4.138130e-016	-3.614801e-021
	5	0.000000e+000	1.175464e-008	-2.132585e-011	-2.485640e-015	3.535714e-019
	6	0.000000e+000	2.045218e-007	-2.001742e-011	-4.217326e-015	-8.965853e-019
	11	0.000000e+000	2.891834e-008	4.645221e-012	-1.114181e-017	-3.826417e-020
	22	0.000000e+000	1.029482e-009	-2.160423e-014	1.886393e-020	1.290161e-022
	32	0.000000e+000	-5.277072e-003	1.078635e-015	3.853875e-018	-9.041445e-023
	33	0.000000e+000	1.288563e-010	1.294359e-013	3.817123e-018	1.912098e-024
45	38	0.000000e+000	4.179479e-009	2.916225e-012	1.437591e-016	1.965879e-019
	39	0.000000e+000	2.193704e-007	3.821860e-011	9.758402e-015	3.844117e-018
	i	E	F	G		
	3	4.102479e-024	-7.556172e-028	0.000000e+000		
	5	9.142663e-023	-1.206849e-026	0.000000e+000		
	6	4.937104e-022	-4.929668e-026	0.000000e+000		
	11	1.329561e-024	2.686166e-029	0.000000e+000		
50	22	-6.301310e-027	1.073452e-031	0.000000e+000		
	32	-2.442106e-026	1.631503e-030	0.000000e+000		
	33	-2.856921e-026	1.805409e-030	0.000000e+000		
	38	-4.239874e-029	7.557044e-027	0.000000e+000		
55	39	-1.364160e-021	9.820195e-026	0.000000e+000		

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Table 1

[Example 1]			
SURFACE No.	GROUP No.	lhb/hl	lΔasph/LI
10	2	1.766	0.001525
12	2	1.023	0.000101
20	3	0.104	0.004805
23	3	0.069	0.003056
25	3	0.114	0.004921
33	3	0.384	0.000364
IL x Øol = 28.408			

Table 2

[Example 2]			
SURFACE No.	GROUP No.	lhb/hl	lΔasph/LI
2	1	4.361	0.001782
5	1	1.844	0.001381
11	2	0.781	0.000373
15	2	0.375	0.000425
20	3	0.037	0.001950
23	3	0.127	0.002467
27	3	0.169	0.000395
32	3	0.300	0.000368
33	3	0.312	0.000621
IL x Øol = 21.068			

Table 3

[Example 3]			
SURFACE No.	GROUP No.	lhb/hl	lΔasph/LI
2	1	3.970	0.000974
7	1	2.357	0.000878
12	2	0.992	0.000365
20	3	0.085	0.004119
23	3	0.078	0.003725
25	3	0.106	0.005833
33	3	0.229	0.001500

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Table 3 (continued)

[Example 3]			
SURFACE No.	GROUP No.	lhb/hl	lΔasph/LI
IL x Øol = 32.030			

Table 4

[Example 4]			
SURFACE No.	GROUP No.	lhb/hl	lΔasph/LI
7	1	1.868	0.004140
8	1	1.712	0.000568
9	2	1.235	0.000355
10	2	1.123	0.001114
18	3	0.057	0.003483
23	3	0.109	0.006516
29	3	0.214	0.000567
30	3	0.268	0.000155
IL x Øol = 26.233			

Table 5

[Example 5]			
SURFACE No.	GROUP No.	lhb/hl	lΔasph/LI
7	1	2.216	0.001748
8	1	1.939	0.000180
9	2	1.085	0.000233
10	2	0.971	0.000429
17	3	0.094	0.000127
18	3	0.077	0.004611
21	3	0.093	0.007132
22	3	0.110	0.001873
27	3	0.257	0.000947
28	3	0.387	0.000046
IL x Øol = 25.150			

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Table 6

[Example 6]			
SURFACE No.	GROUP No.	lhb/hl	lΔasph/Ll
13	2	0.883	0.000335
53	5	0.304	0.000542
IL x Øol = 34.291			

Table 7

[Example 7]			
SURFACE No.	GROUP No.	lhb/hl	lΔasph/Ll
10	2	1.221	0.000531
11	2	0.955	0.000226
IL x Øol = 31.965			

Table 8

[Example 8]			
SURFACE No.	GROUP No.	lhb/hl	lΔasph/Ll
3	1	2.991	0.000317
4	1	2.691	0.000209
9	2	1.387	0.000178
10	2	1.233	0.000040
20	3	0.507	0.000460
35	5	0.042	0.000251
47	5	0.311	0.000072
IL x Øol = 30.670			

Table 9

[Example 9]			
SURFACE No.	GROUP No.	lhb/hl	lΔasph/Ll
3	1	2.944	0.001305
8	2	1.347	0.000952
12	3	0.495	0.000591
18	4	0.245	0.000983

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Table 9 (continued)

[Example 9]			
SURFACE No.	GROUP No.	lhb/hl	lΔasph/LI
22	5	0.051	0.001685
25	5	0.128	0.002088
31	5	0.275	0.001076
IL x Øol = 24.425			

Table 10

[Example 10]			
SURFACE No.	GROUP No.	lhb/hl	lΔasph/LI
3	1	2.870	0.000521
4	1	2.555	0.000844
9	2	1.337	0.000677
10	2	1.212	0.000634
13	3	0.610	0.004306
14	3	0.561	0.002989
19	4	0.267	0.000720
20	4	0.233	0.000588
21	5	0.042	0.000371
22	5	0.061	0.002088
25	5	0.133	0.003329
26	5	0.151	0.000751
IL x Øol = 25.020			

Table 11

[Example 11]			
SURFACE No.	GROUP No.	lhb/hl	lΔasph/LI
12	2	2.074	0.000703
13	2	1.847	0.000539
29	4	0.195	0.001078
32	4	0.082	0.000153
47	5	0.340	0.000407
IL x Øol = 35.737			

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Table 12

[Example 12]			
SURFACE No.	GROUP No.	lhb/hl	lΔasph/LI
3	1	2.955	0.000154
8	2	1.712	0.000505
9	2	1.403	0.000303
33	5	0.208	0.000070
52	7	0.457	0.000321
IL x Øol = 51.483			

Table 13

[Example 13]			
SURFACE No.	GROUP No.	lhb/hl	lΔasph/LI
19	4	0.663	0.000228
21	4	0.504	0.000003
49	7	0.120	0.002189
IL x Øol = 49.149			

Table 14

[Example 14]			
SURFACE No.	GROUP No.	lhb/hl	lΔasph/LI
3	1	3.061	0.000822
8	2	1.691	0.000950
13	3	0.962	0.000358
43	7	0.318	0.000784
IL x Øol = 35.577			

Table 15

[Example 15]			
SURFACE No.	GROUP No.	lhb/hl	lΔasph/LI
2	1	4.345	0.000742
8	2	1.491	0.000214
10	3	0.867	0.002127

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Table 15 (continued)

[Example 15]			
SURFACE No.	GROUP No.	I _{hb} /h _l	I _{Δasph} /L _I
15	4	0.422	0.000665
18	5	0.263	0.001040
25	6	0.015	0.000453
30	7	0.114	0.000968
39	7	0.341	0.000253
IL x Ø _{ol} = 34.550			

Table 16

[Example 16]			
SURFACE No.	GROUP No.	I _{hb} /h _l	I _{Δasph} /L _I
1	1	4.822	0.002485
2	1	4.040	0.000098
3	2	2.368	0.001695
4	2	2.136	0.001942
9	4	0.719	0.000030
10	4	0.655	0.000473
33	7	0.358	0.000358
34	7	0.590	0.001244
IL x Ø _{ol} = 29.054			

Table 17

[Example 17]			
SURFACE No.	GROUP No.	I _{hb} /h _l	I _{Δasph} /L _I
2	1	5.341	0.000029
13	2	1.224	0.000386
27	5	0.248	0.000321
34	6	0.856	0.000547
47	7	7.731	0.000533
IL x Ø _{ol} = 21.930			

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Table 18

[Example 18]			
SURFACE No.	GROUP No.	lhb/hl	lΔasph/LI
2	1	4.030	0.001160
5	1	1.475	0.004369
10	2	0.634	0.001383
12	2	0.345	0.000287
19	3	0.089	0.003157
IL x Øol = 19.546			

Table 19

[Example 19]			
SURFACE No.	GROUP No.	lhb/hl	lΔasph/LI
1	1	2.101	0.000237
2	1	1.999	0.000351
8	2	1.018	0.002759
9	2	0.594	0.000913
10	2	0.523	0.001881
16	3	0.062	0.004013
21	3	0.112	0.005985
27	3	0.211	0.000182
IL x Øol = 26.006			

Table 20

[Example 20]			
SURFACE No.	GROUP No.	lΔasph/LI	lhb/hl
5	1	5.0e ⁻⁴	2.51
10	2	1.8e ⁻³	1.66
15	3	2.9e ⁻⁴	0.73
IL x Øol = 23.85			

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Table 21

[Example 21]			
SURFACE No.	GROUP No.	$I\Delta_{asph/LI}$	$I_{hb/hI}$
2	1	$8.2e^{-4}$	2.92
10	2	$7.0e^{-4}$	0.91
11	2	$6.4e^{-4}$	0.72
$IL \times \varnothing ol = 31.67$			

Table 22

[Example 22]			
SURFACE No.	GROUP No.	$I\Delta_{asph/LI}$	$I_{hb/hI}$
3	1	$1.0e^{-3}$	2.63
8	2	$1.9e^{-3}$	1.53
12	3	$4.0e^{-5}$	0.67
$IL \times \varnothing ol = 22.55$			

Table 23

[Example 23]			
SURFACE No.	GROUP No.	$I\Delta_{asph/LI}$	$I_{hb/hI}$
3	1	$8.2e^{-4}$	2.71
6	2	$7.0e^{-4}$	1.13
8	2	$6.4e^{-4}$	0.78
10	3	$6.7e^{-4}$	0.46
$IL \times \varnothing ol = 27.70$			

Table 24

[Example 24]			
SURFACE No.	GROUP No.	$I\Delta_{asph/LI}$	$I_{hb/hI}$
1	1	$3.2e^{-3}$	4.66
2	1	$1.3e^{-3}$	3.35
5	2	$1.4e^{-3}$	1.03
6	2	$5.3e^{-4}$	0.90
$IL \times \varnothing ol = 30.58$			

Table 25

[Example 25]			
SURFACE No.	GROUP No.	$I\Delta\text{asph/LI}$	$I\text{hb/hI}$
2	1	1.5e^{-3}	4.35
3	2	2.9e^{-4}	2.94
7	3	5.4e^{-4}	1.76
11	4	6.6e^{-4}	0.59
17	6	8.4e^{-5}	0.04
23	7	1.7e^{-3}	0.10
32	7	4.1e^{-4}	0.31
$IL \times \varnothing_{ol} = 24.79$			

Table 26

[Example 26]			
SURFACE No.	GROUP No.	$I\Delta\text{asph/LI}$	$I\text{hb/hI}$
2	1	3.5e^{-3}	4.33
3	2	2.4e^{-3}	2.98
7	3	7.2e^{-4}	1.38
11	4	1.8e^{-4}	0.42
19	6	4.7e^{-4}	0.03
25	7	1.8e^{-3}	0.12
34	7	1.8e^{-4}	0.45
$IL \times \varnothing_{ol} = 24.58$			

Table 27

[Example 27]			
SURFACE No.	GROUP No.	$I\Delta\text{asph/LI}$	$I\text{hb/hI}$
2	1	5.2e^{-4}	4.83
6	2	4.6e^{-4}	2.35
8	2	1.8e^{-3}	1.77
10	3	2.4e^{-3}	1.10
17	4	1.2e^{-3}	0.43
23	5	1.0e^{-3}	0.22
31	7	7.1e^{-5}	0.06

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Table 27 (continued)

[Example 27]			
SURFACE No.	GROUP No.	$l\Delta\text{asph}/l_i$	l_{hb}/h_l
38	7	$3.4e^{-4}$	0.30
$IL \times \varnothing ol = 36.28$			

Table 28

[Example 28]			
SURFACE No.	GROUP No.	$l\Delta\text{asph}/l_i$	l_{hb}/h_l
3	1	$6.5e^{-4}$	4.24
5	2	$1.0e^{-3}$	2.51
6	2	$1.1e^{-3}$	2.21
11	3	$1.6e^{-3}$	1.13
22	5	$1.6e^{-4}$	0.26
32	7	$1.0e^{-3}$	0.11
33	7	$4.7e^{-4}$	0.13
38	7	$5.8e^{-4}$	0.28
39	7	$1.4e^{-3}$	0.41
$IL \times \varnothing ol = 34.21$			

[0604] Figure 89 is a schematic view of a main portion of a semiconductor device manufacturing system which uses a projection optical system according to the present invention. The manufacturing system of this embodiment is arranged to produce semiconductor devices, by printing a circuit pattern formed on a reticle or photomask (first object), on a wafer or photosensitive substrate (second object). Generally, the system includes a projection optical system, a mask accommodating unit, a mask inspection unit, and a controller, all of which are disposed in a clean room.

[0605] Denoted in Figure 89 at 1 is an excimer laser as a light source, and denoted at 2 is an illumination optical system which is provided as a unit. A reticle or mask (first object) 3 is placed at an exposure position EP, and then the mask is illuminated from the above with a predetermined numerical aperture (NA). Denoted at 909 is a projection optical system according to Numerical Example 1 of Figure 1, for example, and it serves to project a circuit pattern of the reticle 3 onto a silicon substrate (wafer) 7 and to print the pattern thereon.

[0606] Denoted at 900 is an alignment system for aligning the reticle 3 and the wafer 7, prior to execution of the exposure process. The alignment system 900 includes at least one reticle observation microscope system. Denoted at 911 is a wafer stage. The elements described above are components of the projection exposure apparatus.

[0607] Denoted at 914 is a mask accommodating unit, for accommodating plural masks therein. Denoted at 913 is an inspection unit for inspecting presence/absence of any foreign particles on masks. This inspection unit 913 is used to perform particle inspection when a selected mask is moved out of the mask accommodating unit 914, and before it is fed to the exposure position EP.

[0608] The controller 918 serves to control the whole sequence of the system. Specifically, it controls the sequences for operations of the accommodating unit 914 and the inspection unit 913, as well as basic operations of the projection exposure apparatus, such as alignment operation, exposure operation and wafer stepwise motion, for example.

[0609] Next, an embodiment of a semiconductor device manufacturing method based on such device manufacturing system described above, will be explained.

[0610] Figure 90 is a flow chart of procedure for manufacture of microdevices such as semiconductor chips (e.g. ICs or LSIs), liquid crystal panels, or CCDs, for example.

[0611] Step 1 is a design process for designing a circuit of a semiconductor device. Step 2 is a process for making a mask on the basis of the circuit pattern design. Step 3 is a process for preparing a wafer by using a material such as

silicon. Step 4 is a wafer process (called a pre-process) wherein, by using the so prepared mask and wafer, circuits are practically formed on the wafer through lithography. Step 5 subsequent to this is an assembling step (called a post-process) wherein the wafer having been processed by step 4 is formed into semiconductor chips. This step includes an assembling (dicing and bonding) process and a packaging (chip sealing) process. Step 6 is an inspection step wherein operation check, durability check and so on for the semiconductor devices provided by step 5, are carried out. With these processes, semiconductor devices are completed and they are shipped (step 7).

[0612] Figure 91 is a flow chart showing details of the wafer process.

[0613] Step 11 is an oxidation process for oxidizing the surface of a wafer. Step 12 is a CVD process for forming an insulating film on the wafer surface. Step 13 is an electrode forming process for forming electrodes upon the wafer by vapor deposition. Step 14 is an ion implanting process for implanting ions to the wafer. Step 15 is a resist process for applying a resist (photosensitive material) to the wafer. Step 16 is an exposure process for printing, by exposure, the circuit pattern of the mask on the wafer through the exposure apparatus described above. Step 17 is a developing process for developing the exposed wafer. Step 18 is an etching process for removing portions other than the developed resist image. Step 19 is a resist separation process for separating the resist material remaining on the wafer after being subjected to the etching process. By repeating these processes, circuit patterns are superposedly formed on the wafer.

[0614] With these processes, high density microdevices can be manufactured.

[0615] In the embodiment described above, the projection exposure apparatus is of the type that the whole circuit pattern of a reticle 3 is printed at once on a wafer. In place of it, the present invention is applicable to a projection exposure apparatus of scanning type wherein light from a laser light source is projected to a portion of a circuit pattern of a reticle through an illumination optical system and, while the reticle and a wafer are scanningly moved relatively to the projection optical system and in a direction perpendicular to the optical axis direction of the projection optical system, the circuit pattern of the reticle is projected and printed on the wafer.

[0616] While the invention has been described with reference to the structures disclosed herein, it is not confined to the details set forth and this application is intended to cover such modifications or changes as may come within the purposes of the improvements or the scope of the following claims.

Claims

1. A projection optical system, comprising:

a plurality of positive lens groups having a positive refractive power; and
at least one negative lens group having a negative refractive power;
wherein, when L is a conjugate distance of said projection optical system and $\sum \phi_0$ is the sum of powers of the
or each negative lens group, a relation

$$|L \times \sum \phi_0| > 17 \quad (\sum \phi_0 = \sum \phi_{0i} \text{ where } \phi_{0i} \text{ is the power of the } i\text{-th negative group})$$

is satisfied;

wherein, when h is a height of an axial marginal light ray and h_b is a height of a most abaxial chief ray, at least
two aspherical surfaces are formed on surfaces which satisfy a relation

$$|h_b/h| > 0.35;$$

wherein, when $\Delta ASPH$ is an aspherical amount of each aspherical surface, a relation

$$|\Delta ASPH/L| > 1.0 \times 10^{-6}$$

is satisfied; and

wherein said at least two aspherical surfaces include regions in which, from a central portion toward a peripheral portion of the surface, their local curvature powers change with mutually opposite signs.

2. A projection optical system according to Claim 1, wherein said at least two aspherical surfaces are formed on those surfaces up to one, in an order from the object side, which satisfies a relation

$$|h_b/h| > 0.35.$$

3. A projection optical system according to Claim 1 or 2, wherein at least one of said at least two aspherical surfaces is provided in a negative lens group and includes a region in which, from the central portion to the peripheral portion

of the surface, the local curvature power thereof gradually increases in the negative direction or gradually decreases in the positive direction.

4. A projection optical system according to any one of Claims 1 - 3, wherein relations

$$|L \times \varnothing_0| < 70$$

$$|h_b/h| < 15$$

$$|\Delta\text{ASPH}/L| < 0.02$$

are satisfied.

5. A projection optical system, comprising:

a plurality of positive lens groups having a positive refractive power; and
at least one negative lens group having a negative refractive power;
wherein, when L is a conjugate distance of said projection optical system and \varnothing_0 is the sum of powers of the
or each negative lens group, a relation

$$|L \times \varnothing_0| > 17$$

is satisfied;

wherein, when h is a height of an axial marginal light ray and h_b is a height of a most abaxial chief ray, at least
one aspherical surface is formed on a surface in the negative lens group which satisfies a relation

$$|h_b/h| > 0.35;$$

wherein, when ΔASPH is an aspherical amount of the aspherical surface, a relation

$$|\Delta\text{ASPH}/L| > 1.0 \times 10^{-6}$$

is satisfied; and

wherein said at least one aspherical surface includes a region in which, from a central portion toward a peripheral portion of the surface, a local curvature power thereof increases in the negative direction or decreases in the positive direction.

6. A projection optical system according to Claim 5, wherein at least one aspherical surface is provided in a positive lens group and is formed upon one of the surfaces up to one, in an order from the object side, which satisfies a relation

$$|h_b/h| > 0.35$$

and wherein said at least one aspherical surface includes a region in which, from the central portion to the peripheral portion of the surface, the local curvature power thereof gradually increases in the positive direction or gradually decreases in the negative direction.

7. A projection optical system according to Claim 5 or 6, wherein relations

$$|L \times \varnothing_0| < 70$$

$$|h_b/h| < 15$$

$$|\Delta\text{ASPH}/L| < 0.02$$

are satisfied.

8. A projection optical system, comprising:

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three lens groups of a lens group having a positive refractive power, a lens group having a negative refractive power, and a lens group having a positive refractive power, which are disposed in this order from the object side;

wherein, when L is a conjugate distance of said projection optical system and ϕ_0 is the power of said second negative refractive power lens group, a relation

$$|L \times \phi_0| > 17$$

is satisfied;

wherein, when h is a height of an axial marginal light ray and h_b is a height of a most abaxial chief ray, at least two aspherical surfaces are formed on surfaces which satisfy a relation

$$|h_b/h| > 0.35; \text{ and}$$

wherein, when ΔASPH is an aspherical amount of each aspherical surface, a relation

$$\text{ASPH}/L > 1.0 \times 10^{-6}$$

is satisfied.

9. A projection optical system according to Claim 8, wherein said at least two aspherical surfaces include regions in which, from a central portion toward a peripheral portion of the surface, their local curvature powers change with mutually opposite signs.

10. A projection optical system according to Claim 8 or 9, wherein an aspherical surface is provided in the positive lens group closest to the object side, which aspherical surface includes a region in which, from the central portion to the peripheral portion of the surface, the local curvature power thereof gradually increases in the positive direction or gradually decreases in the negative direction.

11. A projection optical system according to any one of Claims 8 - 10, wherein an aspherical surface is provided in the positive lens group closest to the image plane side, which aspherical surface includes a region in which, from the central portion to the peripheral portion of the surface, the local curvature power thereof gradually increases in the negative direction or gradually decreases in the positive direction.

12. A projection optical system according to any one of Claims 8 - 11, wherein a or each lens group disposed after, in an order from the object side to the image plane side, the sign of an abaxial chief ray height is reversed, has at least one aspherical surface formed thereon.

13. A projection optical system according to any one of Claims 8 - 12, wherein, in the positive lens group disposed closest to the image plane side, a second lens thereof in an order from the image plane side comprises a negative lens having a concave surface facing to the image side, and wherein a lens of that lens group, which lens is closest to the image plane side, comprises a positive lens having a concave surface facing to the image plane side.

14. A projection optical system according to any one of Claims 8 - 13, wherein at least one aspherical lens with an aspherical surface has a plane surface formed on its side opposite to the aspherical surface thereof.

15. A projection optical system according to any one of Claims 8 - 13, wherein each aspherical lens with an aspherical surface has a plane surface formed on its side opposite to the aspherical surface thereof.

16. A projection optical system according to any one of Claims 8 - 13, wherein at least one aspherical lens provided in said projection optical system has two aspherical surfaces formed on the opposite sides thereof.

17. A projection optical system according to any one of Claims 8 - 13, wherein each aspherical lens provided in said projection optical system has two aspherical surfaces formed on the opposite sides thereof.

18. A projection optical system according to any one of Claims 8 - 17, wherein relations

$$|L \times \phi_0| < 70$$

$$|h_b/h| < 15$$

$$|\Delta\text{ASPH}/L| < 0.02$$

are satisfied.

19. A projection optical system, comprising:

a first lens group L1 having a positive refractive power, a second lens group L2 having a negative refractive power, a third lens group L3 having a positive refractive power, a fourth lens group L4 having a negative refractive power, and a fifth lens group L5 having a positive refractive power, which are disposed in this order from the object side;

wherein, when h is a height of an axial marginal light ray and h_b is a height of a most abaxial chief ray, at least two aspherical surfaces are formed on surfaces which satisfy a relation

$$|h_b/h| > 0.35;$$

wherein, when ΔASPH is a largest aspherical amount of each aspherical surface from an optical axis to a lens effective diameter and L is an object-to-image distance, each aspherical surface satisfies a relation

$$|\Delta\text{ASPH}/L| > 1.0 \times 10^{-6}; \text{ and}$$

wherein said aspherical surfaces include regions in which, from a central portion to a peripheral portion of the surface, their local curvature powers change with mutually opposite signs.

20. A projection optical system according to Claim 19, wherein at least one of said at least two aspherical surfaces includes a region in which, from the central portion to the peripheral portion of the surface, the local curvature power thereof gradually increases in the negative direction.

21. A projection optical system according to Claim 18 or 19, wherein at least one of said at least two aspherical surfaces is provided in a lens group having a negative refractive power.

22. A projection optical system, comprising:

a first lens group L1 having a positive refractive power, a second lens group L2 having a negative refractive power, a third lens group L3 having a positive refractive power, a fourth lens group L4 having a negative refractive power, and a fifth lens group L5 having a positive refractive power, which are disposed in this order from the object side;

wherein, when h is a height of an axial marginal light ray and h_b is a height of a most abaxial chief ray, at least one aspherical surface is formed on a surface which satisfies a relation

$$|h_b/h| > 0.35;$$

wherein, when ASPH is a largest aspherical amount of said aspherical surface from an optical axis to a lens effective diameter and L is an object-to-image distance, said aspherical surface satisfies a relation

$$|\Delta\text{ASPH}/L| > 1.0 \times 10^{-6}; \text{ and}$$

wherein said aspherical surface includes a region in which, from a central portion to a peripheral portion of the surface, a local curvature power thereof gradually increases in the negative direction.

23. A projection optical system according to any one of Claim 19 - 22, wherein at least one aspherical lens provided in said projection optical system has a plane surface formed on its side opposite to the aspherical surface thereof.

24. A projection optical system according to any one of Claims 19 - 22, wherein each aspherical lens provided in said projection optical system has a plane surface formed on its side opposite to the aspherical surface thereof.

25. A projection optical system according to any one of Claims 19 - 22, wherein at least one aspherical lens provided

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in said projection optical system has aspherical surfaces formed on the opposite sides thereof.

26. A projection optical system according to any one of Claims 19 - 22, wherein each aspherical lens provided in said projection optical system has aspherical surfaces formed on the opposite sides thereof.

27. A projection optical system according to any one of Claims 19 - 22, wherein relations

$$|h_b/h_l| < 15$$

$$|\Delta\text{ASPH}/L| < 0.02$$

are satisfied.

28. A projection optical system according to any one of Claims 19 - 27, wherein, when L is an object-to-image distance of said projection optical system and $\Sigma\phi_0$ is the sum of powers of the negative lens groups, a relation

$$|L \times \Sigma\phi_0| > 17 \quad (\Sigma\phi_0 = \Sigma\phi_{0i} \text{ where } \phi_{0i} \text{ is the power of the } i\text{-th negative group})$$

is satisfied.

29. A projection optical system according to Claim 28, wherein a relation

$$|L \times \Sigma\phi_0| < 70$$

is satisfied.

30. A projection optical system, comprising:

a first lens group L1 having a positive refractive power, a second lens group L2 having a negative refractive power, a third lens group L3 having a positive refractive power, a fourth lens group L4 having a negative refractive power, a fifth lens group L5 having a positive refractive power, a sixth lens group having a negative refractive power, and a seventh lens group having a positive refractive power, which are disposed in this order from the object side;

wherein one or more aspherical surfaces are formed in said projection optical system; and

wherein, when ASPH is a largest aspherical amount of each aspherical surface from an optical axis to a lens effective diameter and L is an object-to-image distance, at least one aspherical surface satisfies a relation

$$|\Delta\text{ASPH}/L| > 1.0 \times 10^{-6}$$

31. A projection optical system according to Claim 30, wherein at least one aspherical surface is provided between a first lens surface closest to the object side and a stop position.

32. A projection optical system according to Claim 30 or 31, wherein, when h is a height of an axial marginal light ray and h_b is a height of a most abaxial chief ray, at least one aspherical surface is formed on a surface which satisfies a relation

$$|h_b/h_l| > 0.35.$$

33. A projection optical system according to Claim 32, wherein at least two aspherical surface are formed in said projection optical system.

34. A projection optical system according to any one of Claims 30 - 33, wherein the aspherical surface is provided in a lens group having a negative refractive power, and wherein at least one aspherical surface in the lens group of negative refractive power includes a region in which, from a central portion to a peripheral portion of the surface, a local curvature power thereof gradually increases in the negative direction.

35. A projection optical system according to any one of Claims 30 - 34, wherein at least two aspherical surfaces include regions in which, from a central portion to a peripheral portion of the surface, their local curvature powers change

with mutually opposite signs.

36. A projection optical system according to any one of Claim 30 - 35, wherein at least one aspherical lens provided in said projection optical system has a plane surface formed on its side opposite to the aspherical surface thereof.
37. A projection optical system according to any one of Claims 30 - 35, wherein each aspherical lens provided in said projection optical system has a plane surface formed on its side opposite to the aspherical surface thereof.
38. A projection optical system according to any one of Claims 30 - 35, wherein at least one aspherical lens provided in said projection optical system has aspherical surfaces formed on the opposite sides thereof.
39. A projection optical system according to any one of Claims 30 - 35, wherein each aspherical lens provided in said projection optical system has aspherical surfaces formed on the opposite sides thereof.
40. A projection optical system according to any one of Claims 30 - 39, wherein, when L is an object-to-image distance of said projection optical system and \emptyset is the sum of powers of the negative lens groups, a relation

$$|L \times \emptyset_0| > 17 \quad (\emptyset_0 = \sum \emptyset_{oi} \text{ where } \emptyset_{oi} \text{ is the power of the } i\text{-th negative group})$$

is satisfied.

41. A projection optical system according to any one of Claims 30 - 40, wherein a relation

$$|\Delta \text{ASPH}/L| < 0.02$$

is satisfied.

42. A projection optical system according to Claim 32 or 33, wherein a relation

$$|h_b/h| < 15$$

is satisfied.

43. A projection optical system according to Claim 40, wherein a relation

$$|L \times \emptyset_0| < 70$$

is satisfied.

44. A projection exposure apparatus for projecting a pattern of a first object, illuminated with light from a light source, onto a second object by use of a projection optical system as recited in any one of Claims 1 - 43.

45. A projection exposure apparatus for projecting a pattern of a first object, illuminated with light from a light source, onto a second object by use of a projection optical system as recited in any one of Claims 1 - 43, while scanningly moving the first and second objects in a direction perpendicular to an optical axis of said projection optical system, in synchronism with each other and at a speed ratio corresponding to a projection magnification of said projection optical system.

46. A device manufacturing method, comprising the steps of:

exposing a wafer to a device pattern of a reticle by use of a projection exposure apparatus as recited in Claim 44 or 45;
developing the exposed wafer; and
fabricating a device from the exposed and developed wafer.

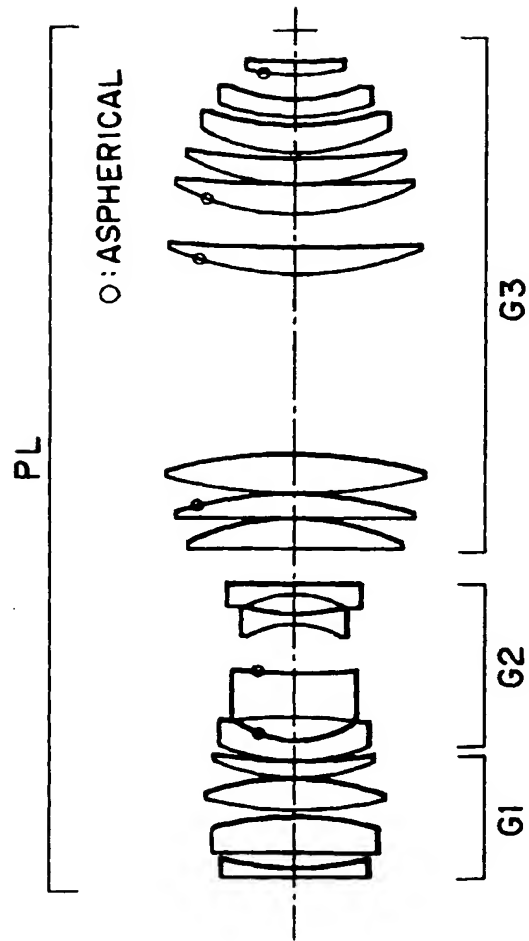


FIG. 1

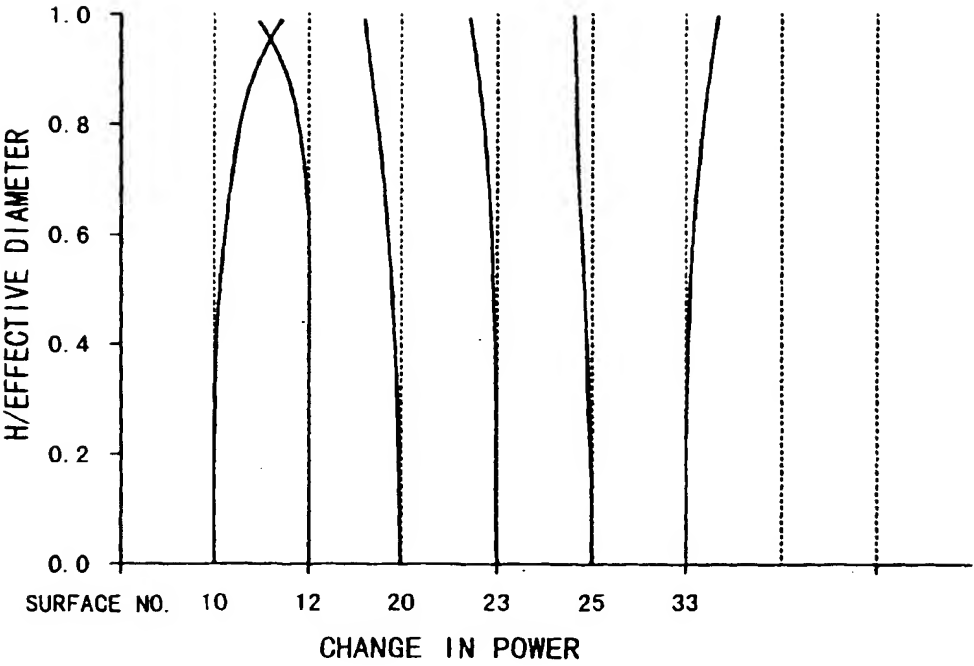


FIG. 2

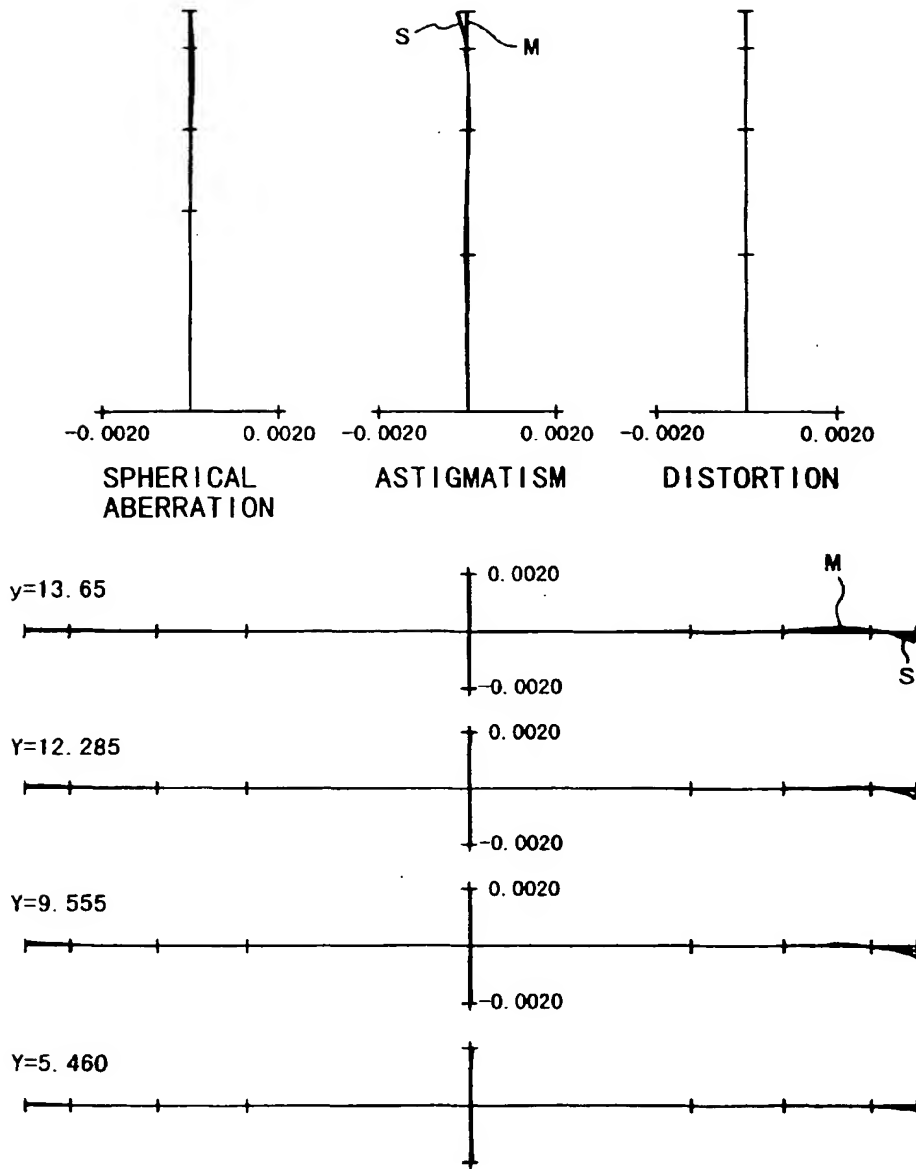


FIG. 3

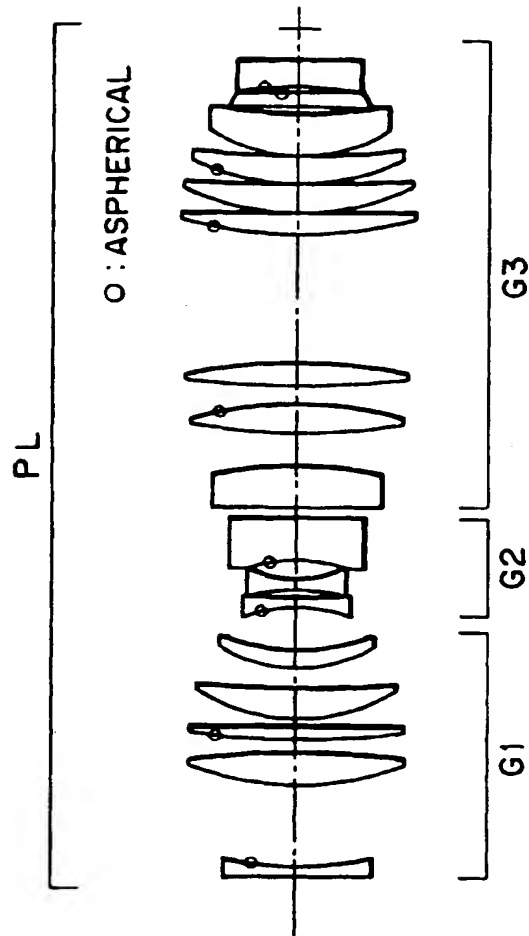


FIG. 4

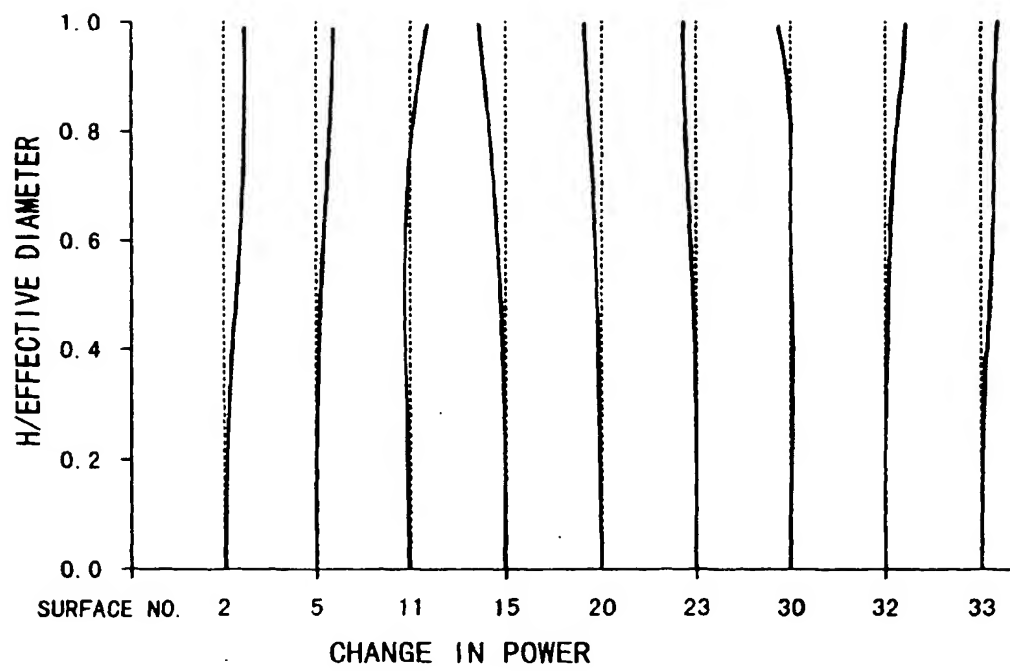


FIG. 5

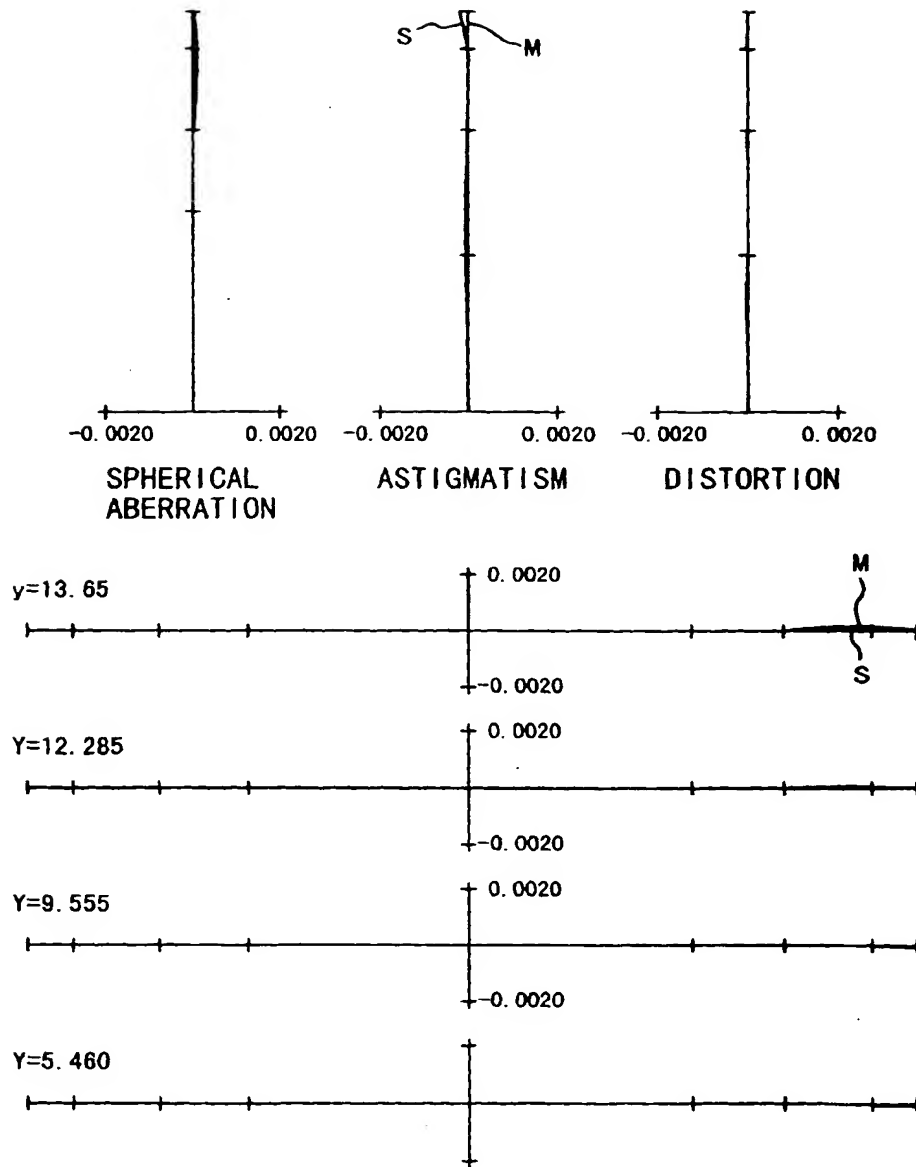


FIG. 6

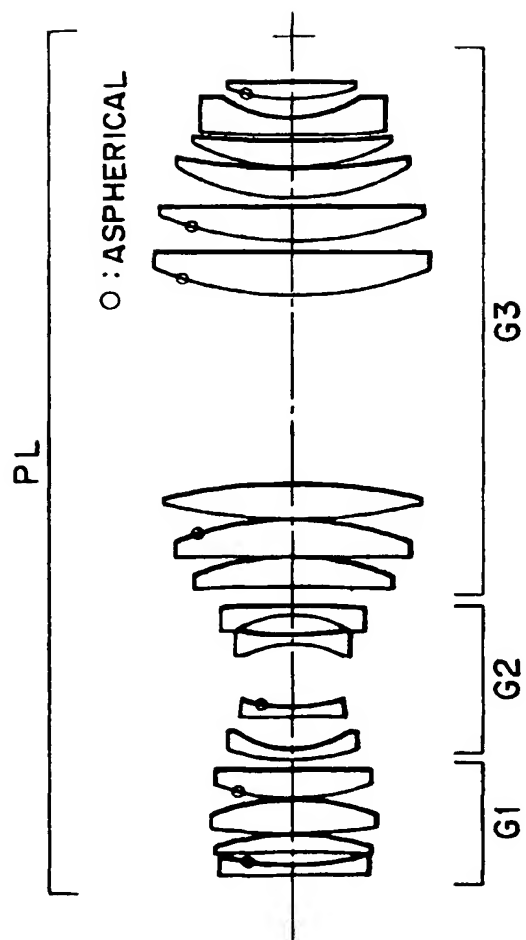


FIG. 7

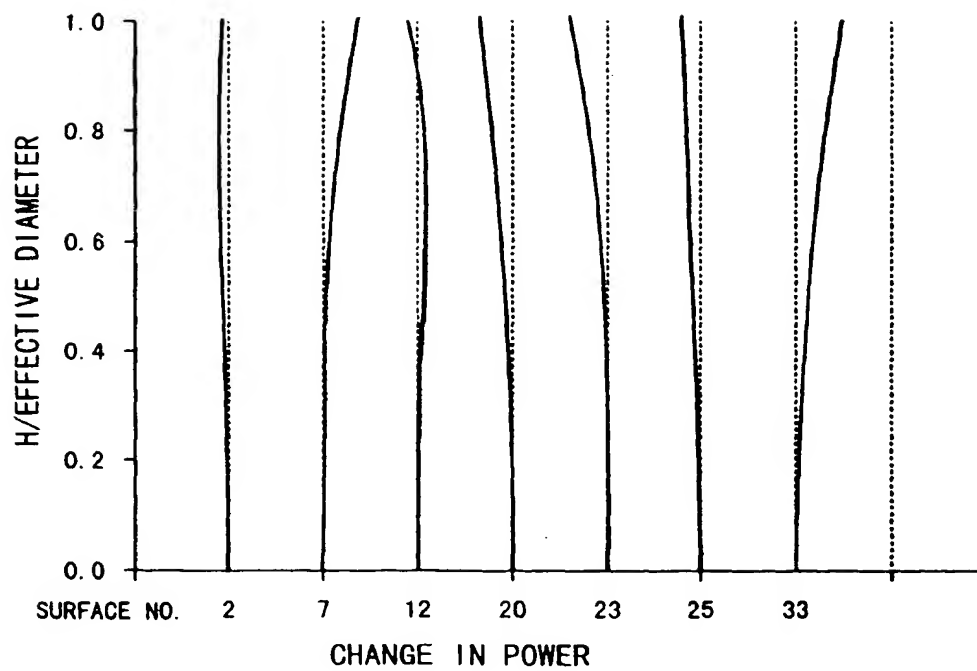


FIG. 8

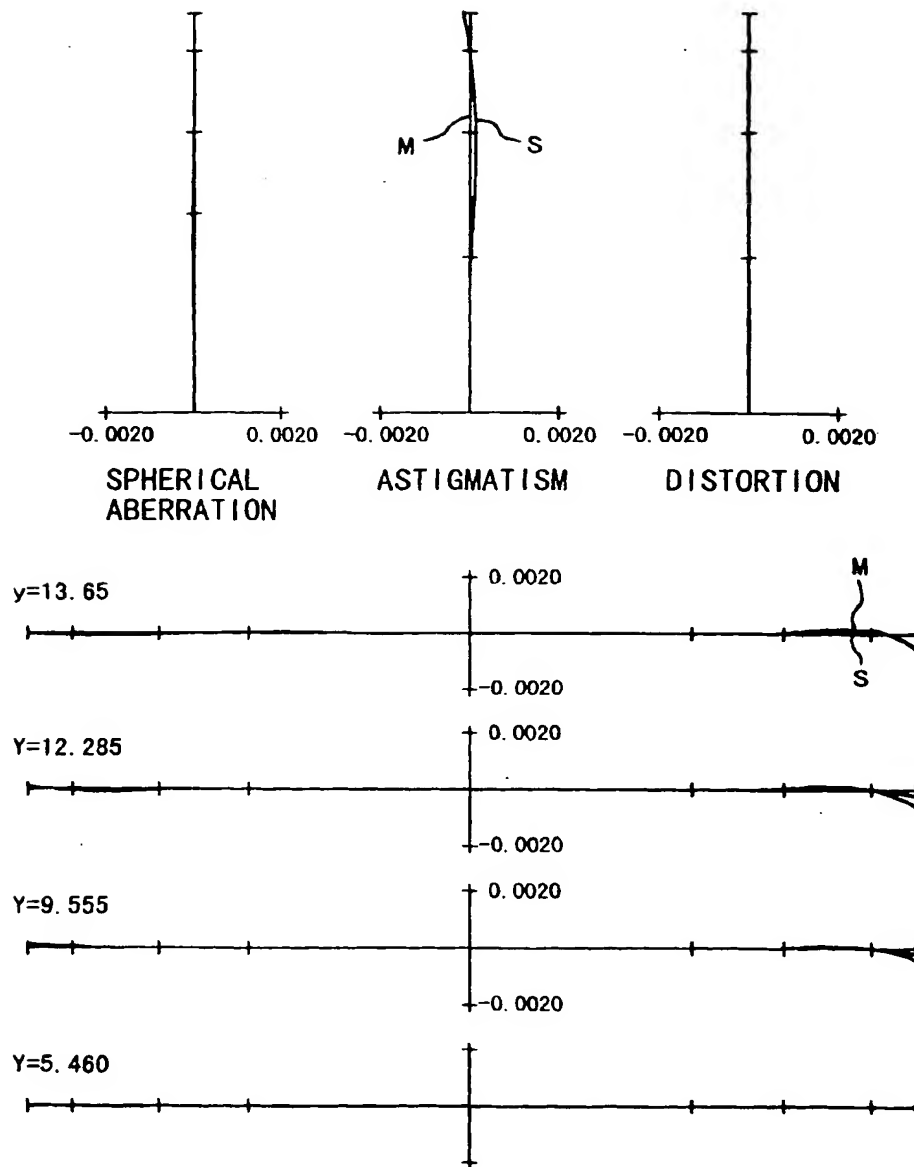


FIG. 9

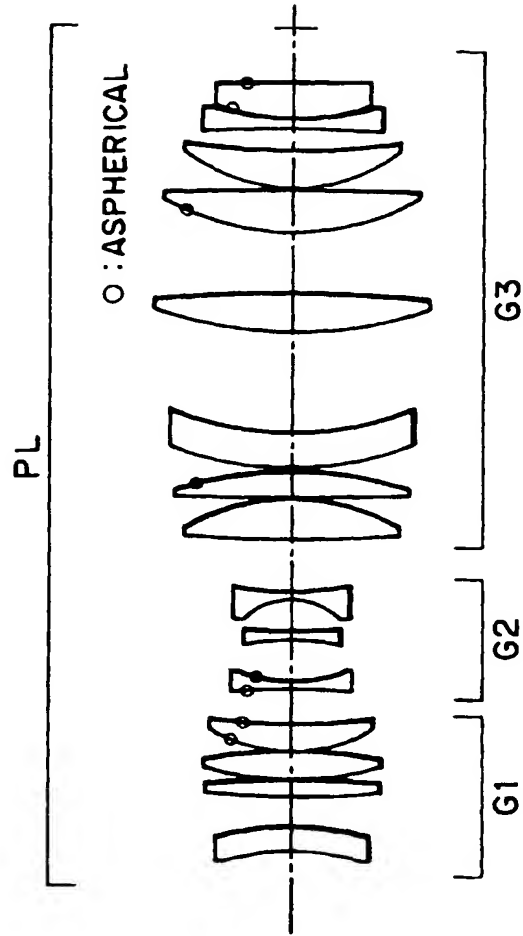


FIG. 10

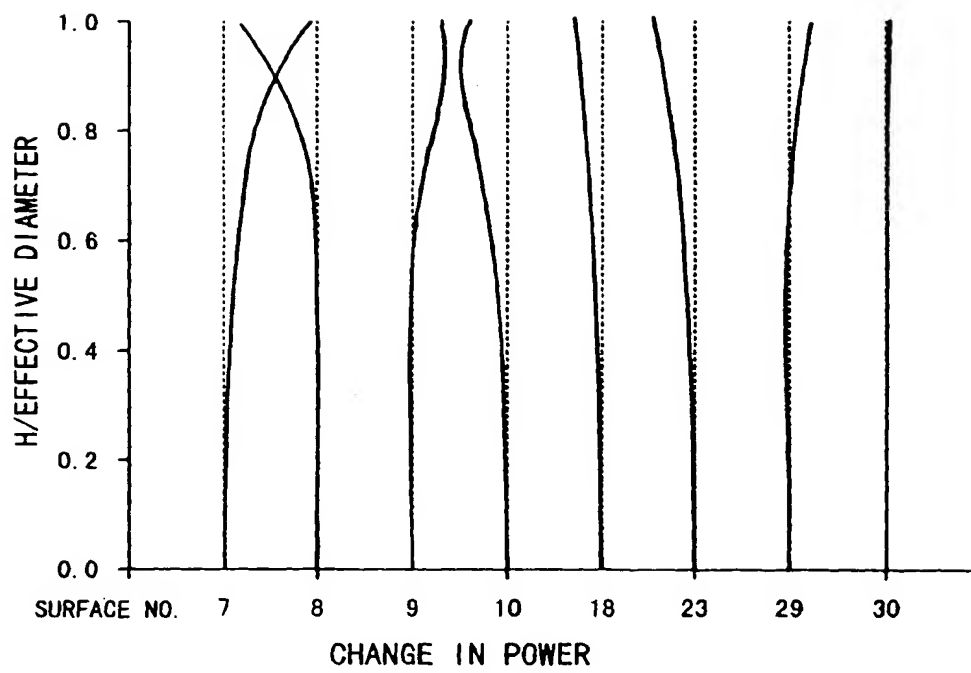


FIG. II

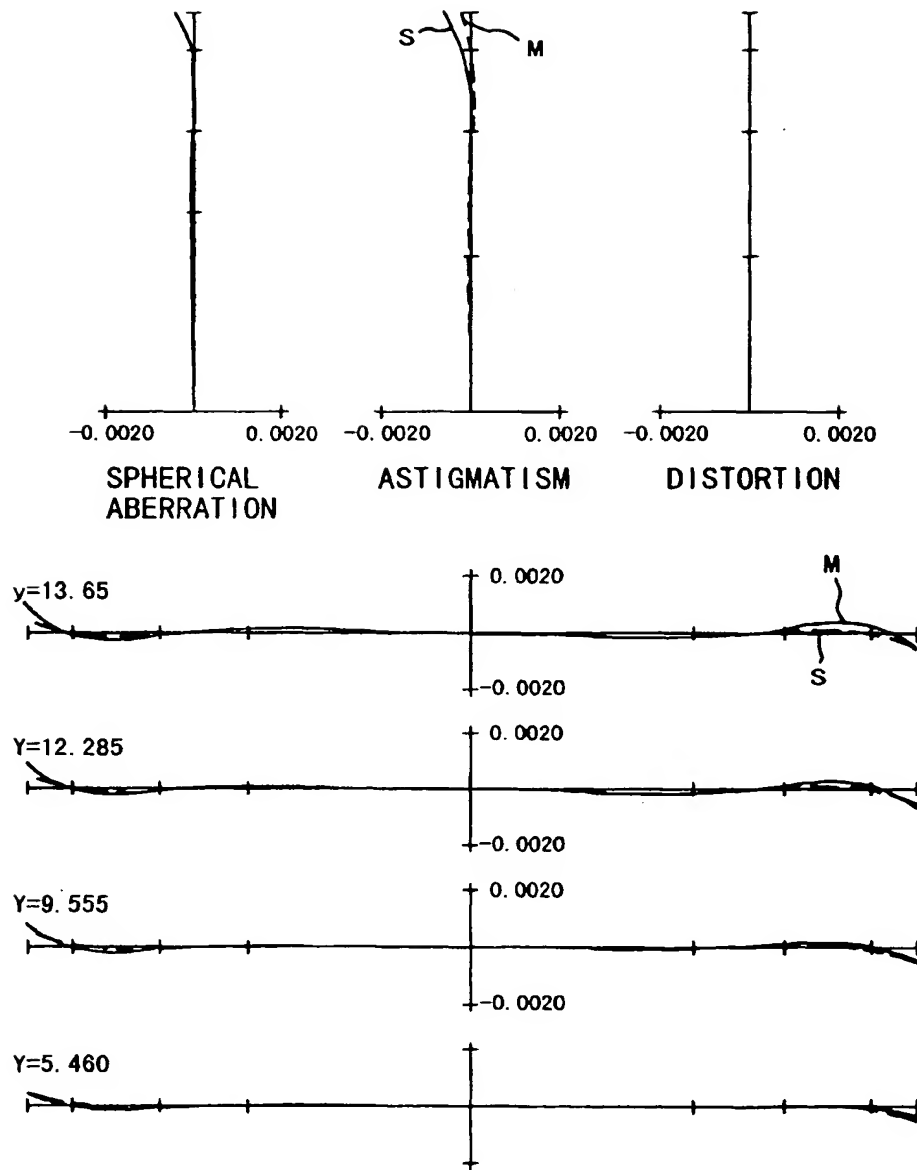


FIG. 12

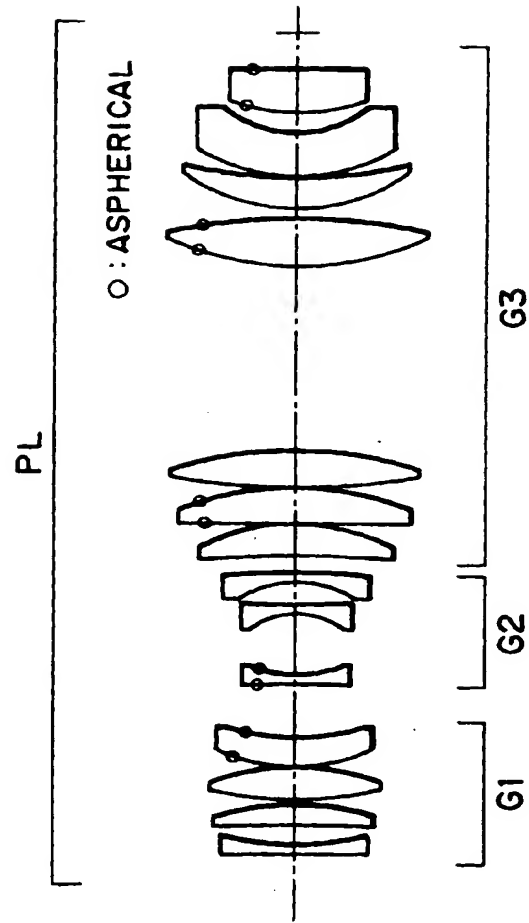


FIG. 13

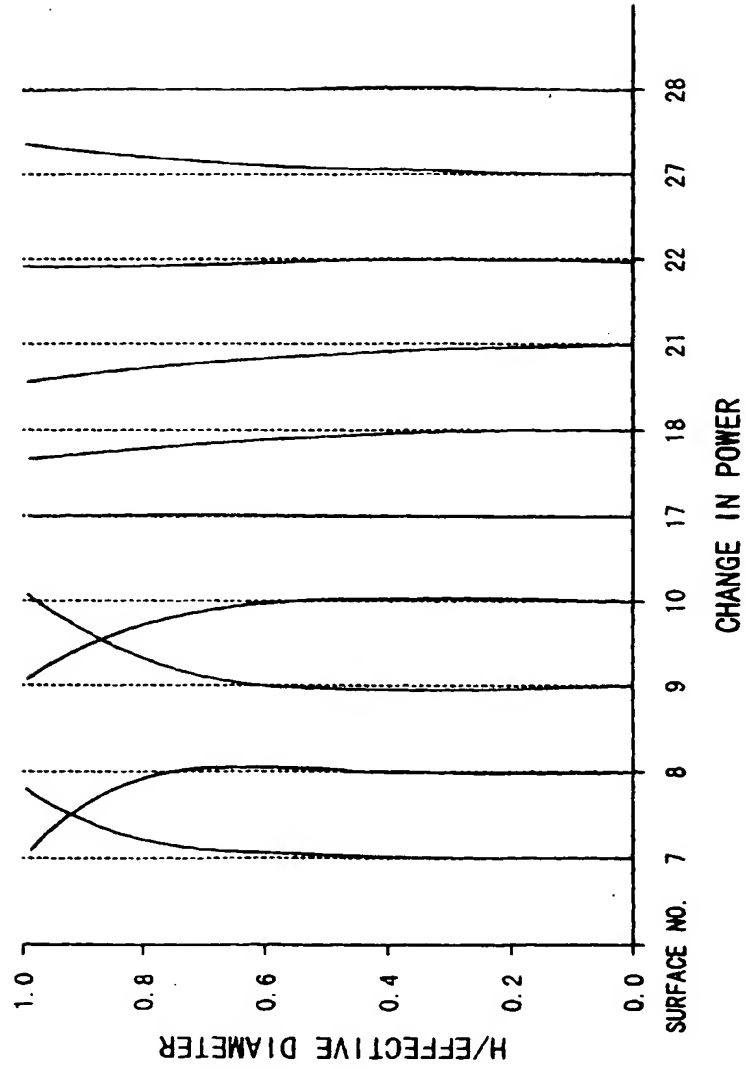


FIG. 14

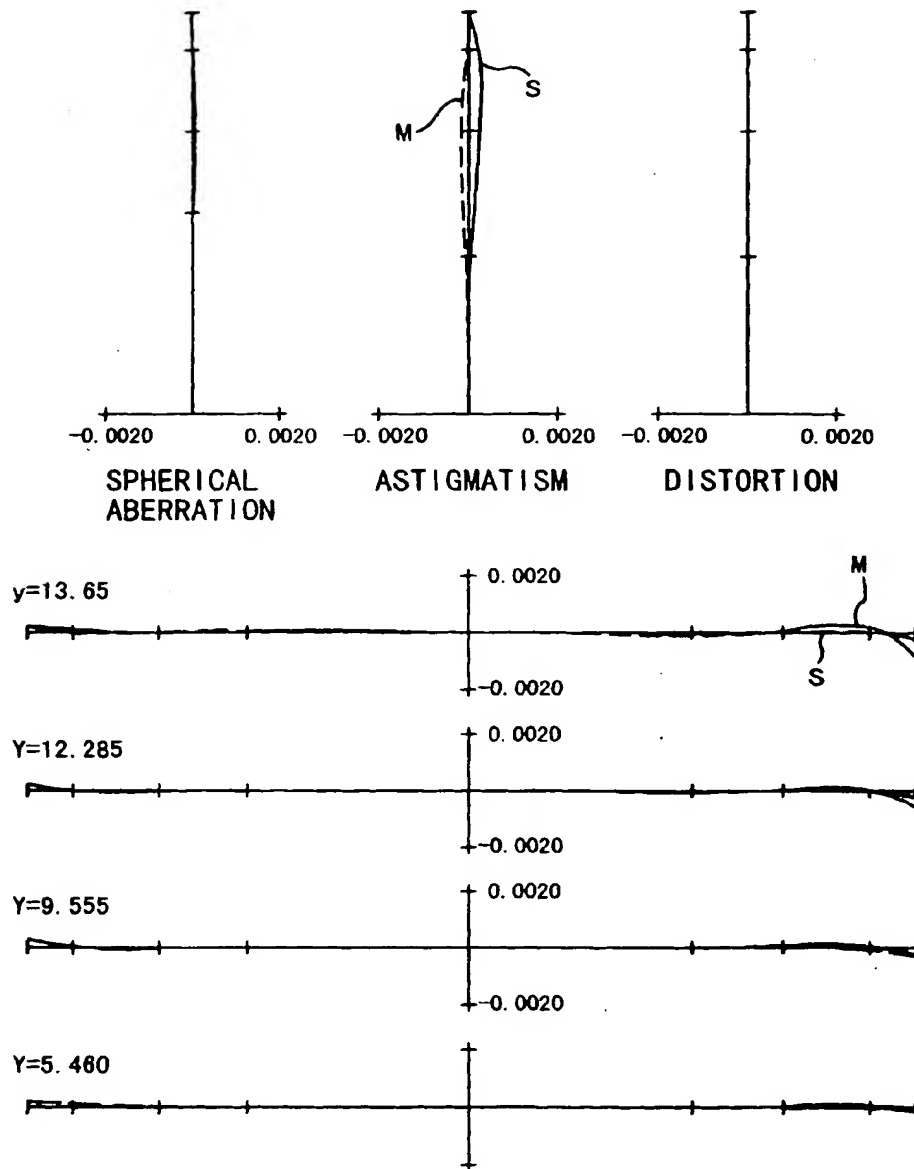


FIG. 15

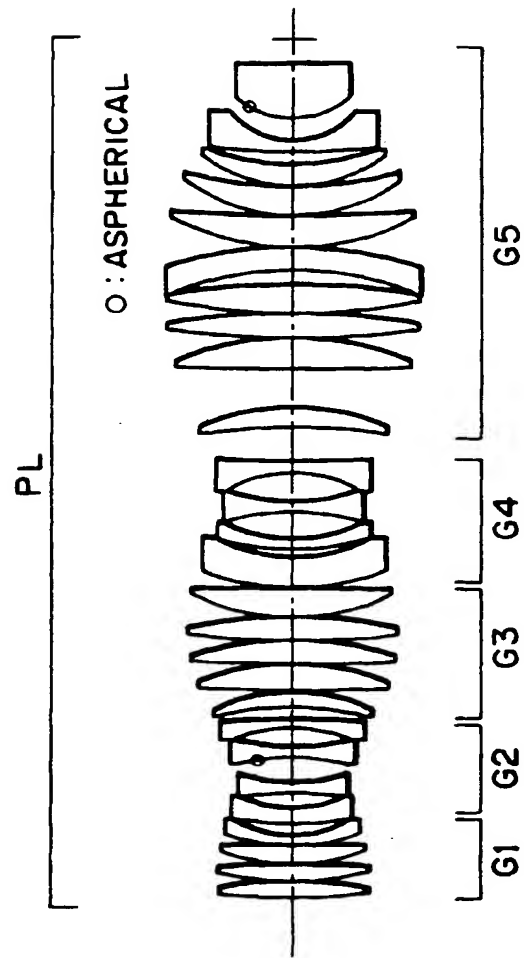


FIG. 16

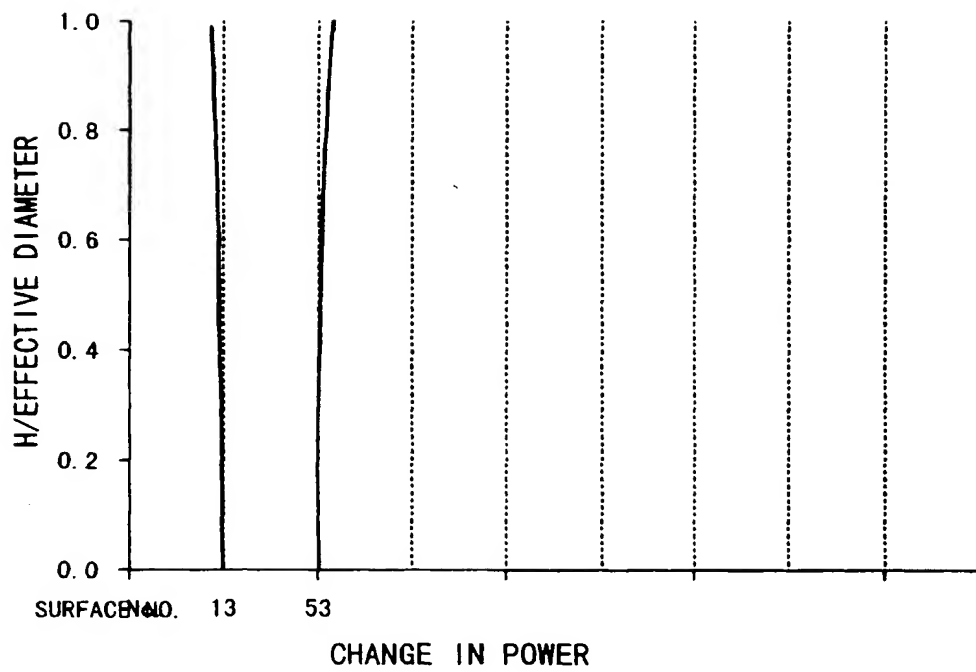


FIG. 17

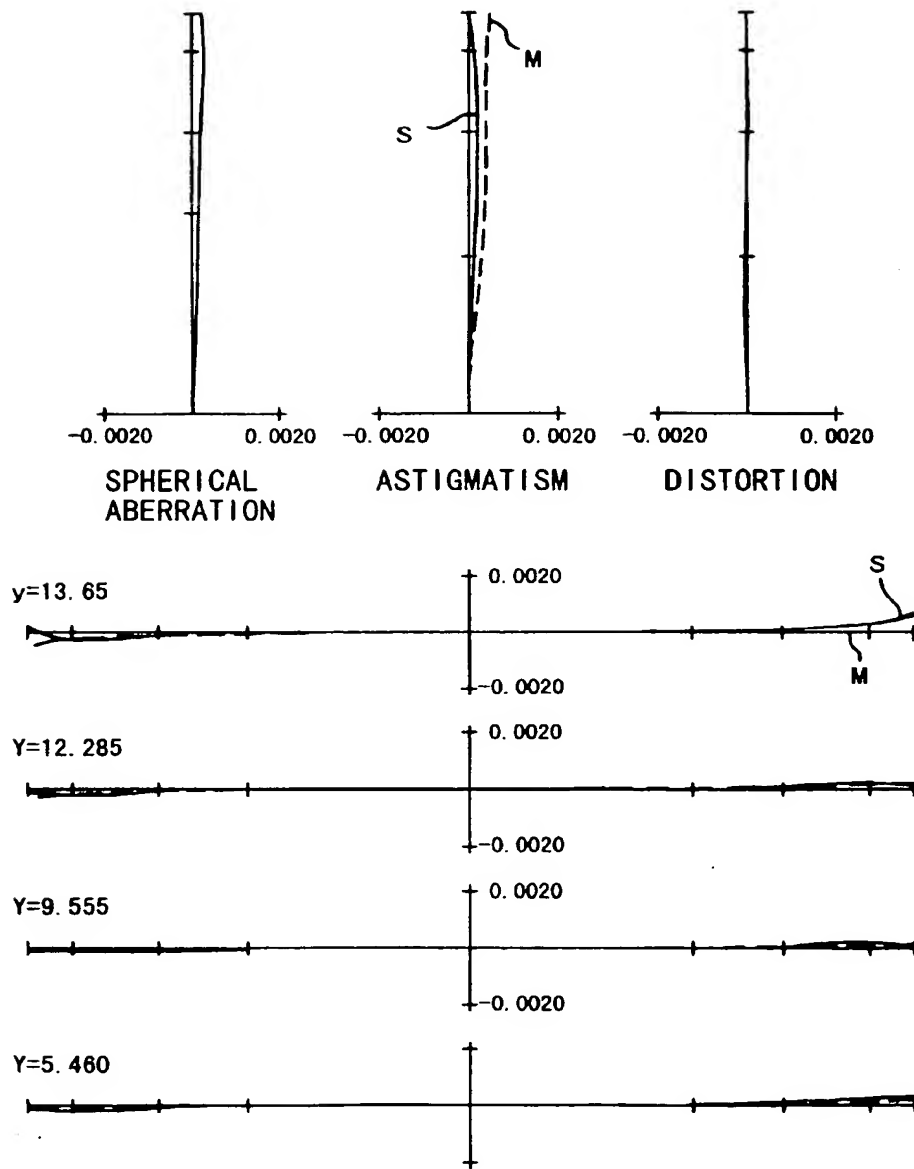


FIG. 18

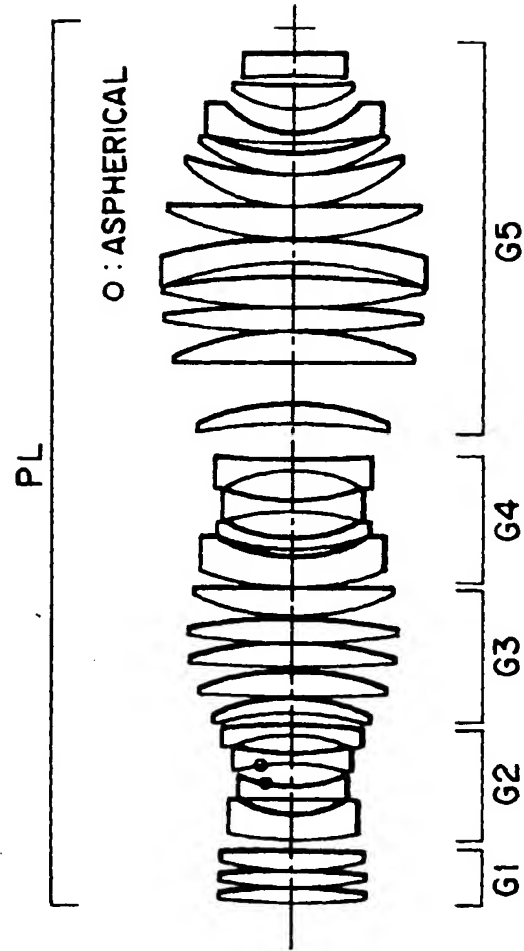


FIG. 19

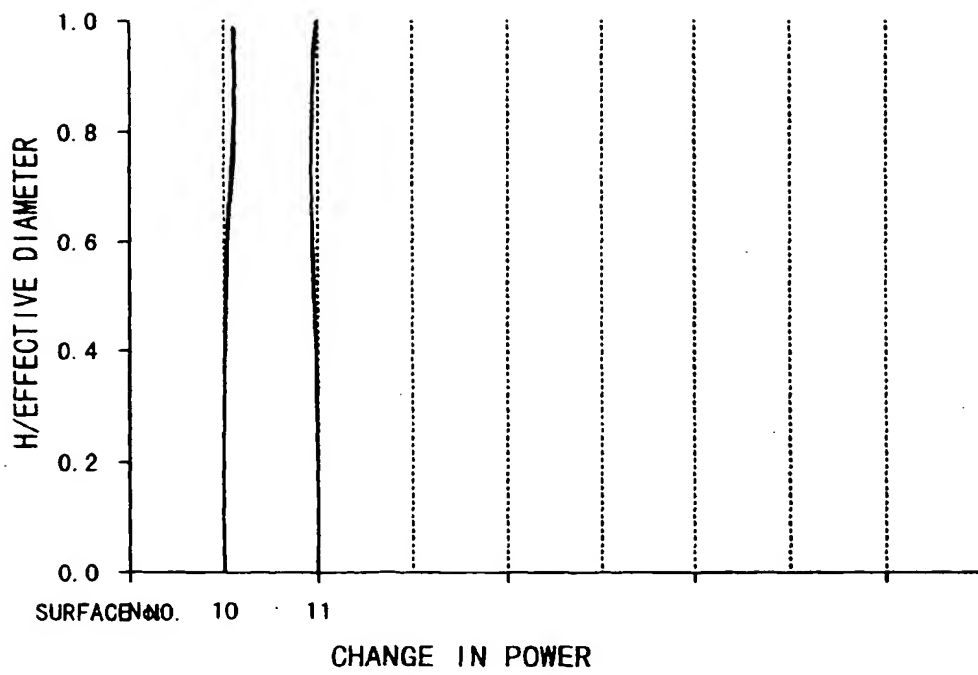


FIG. 20

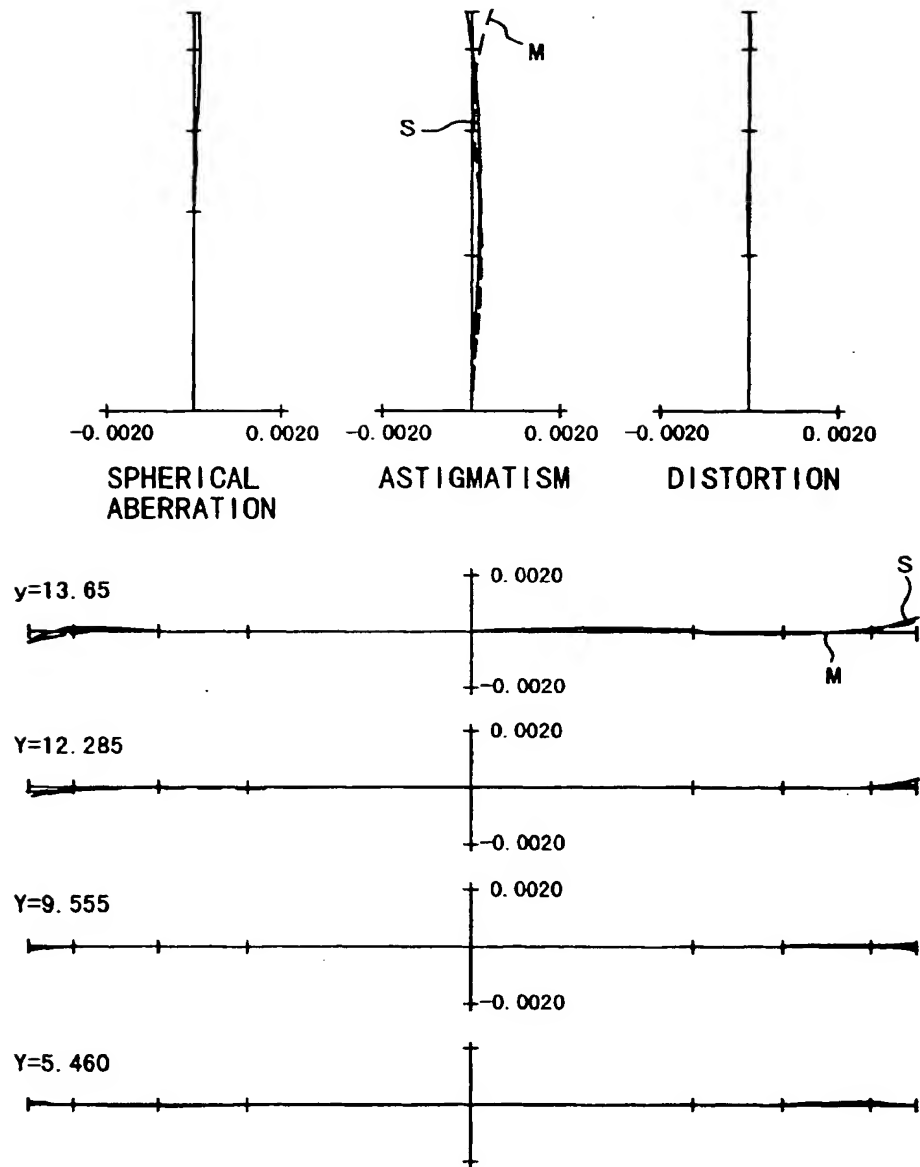


FIG. 21

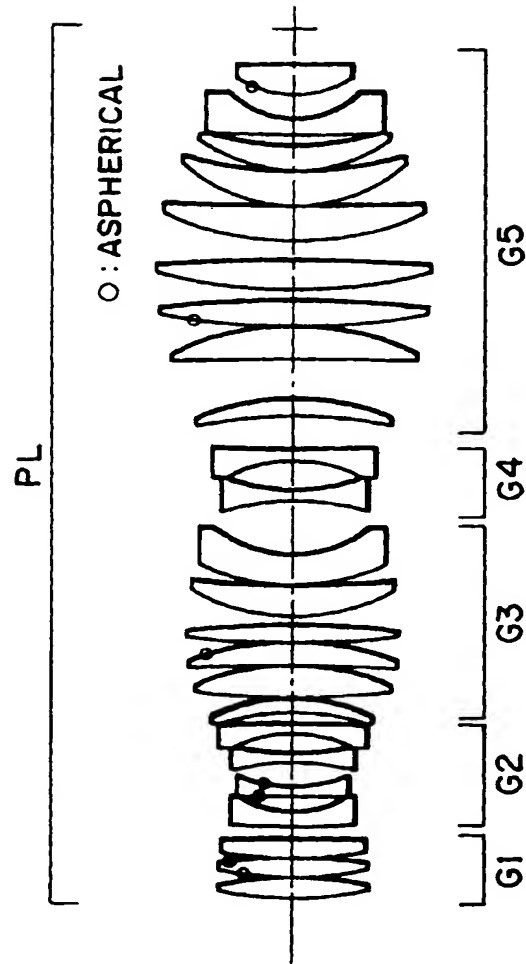


FIG. 22

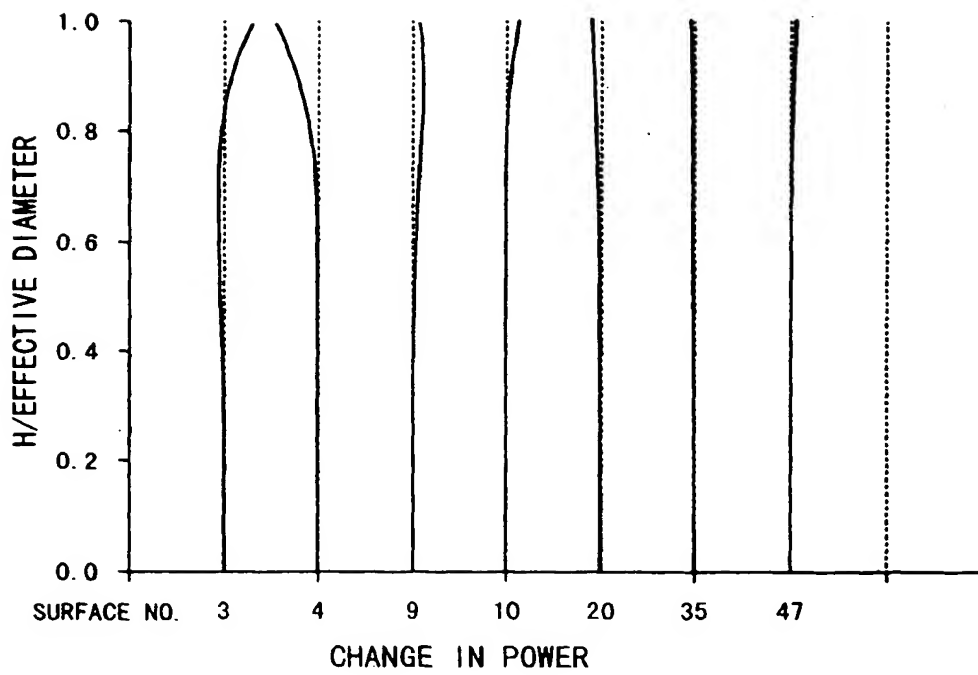


FIG. 23

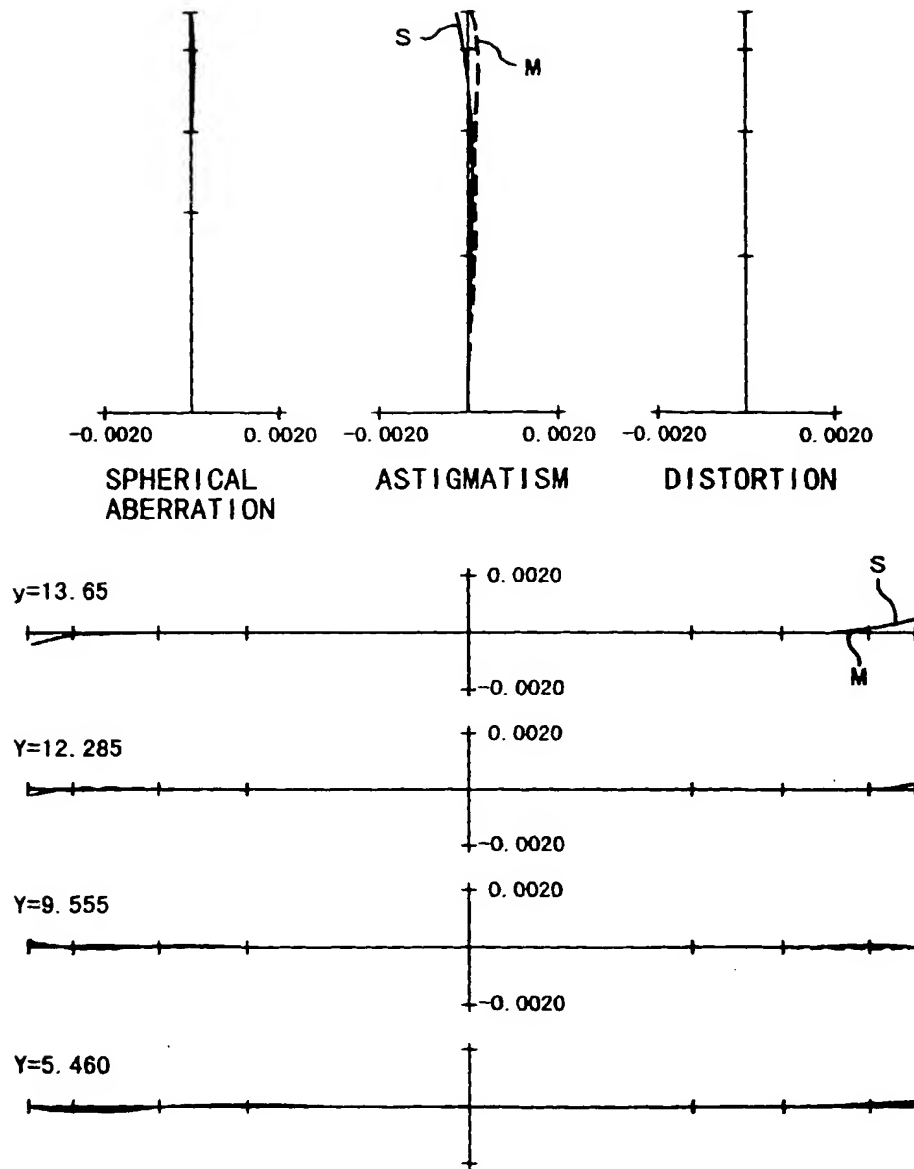


FIG. 24

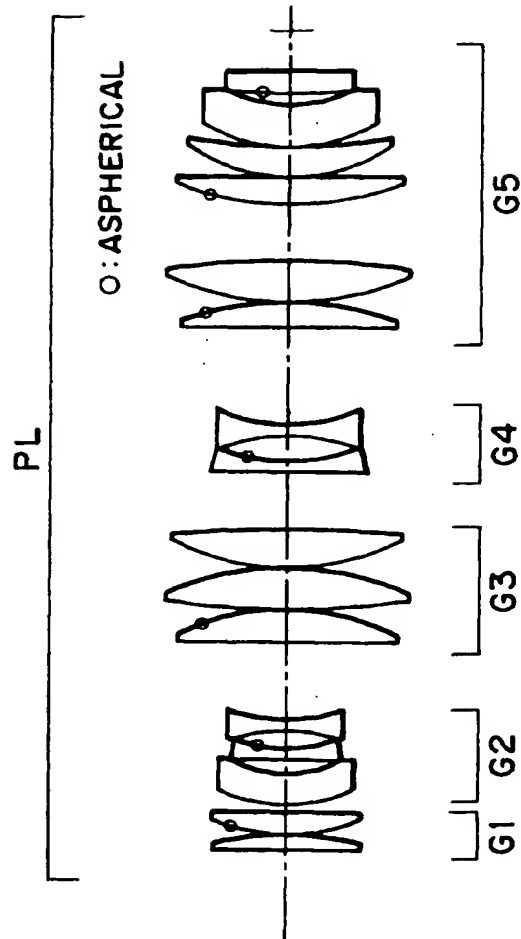


FIG. 25

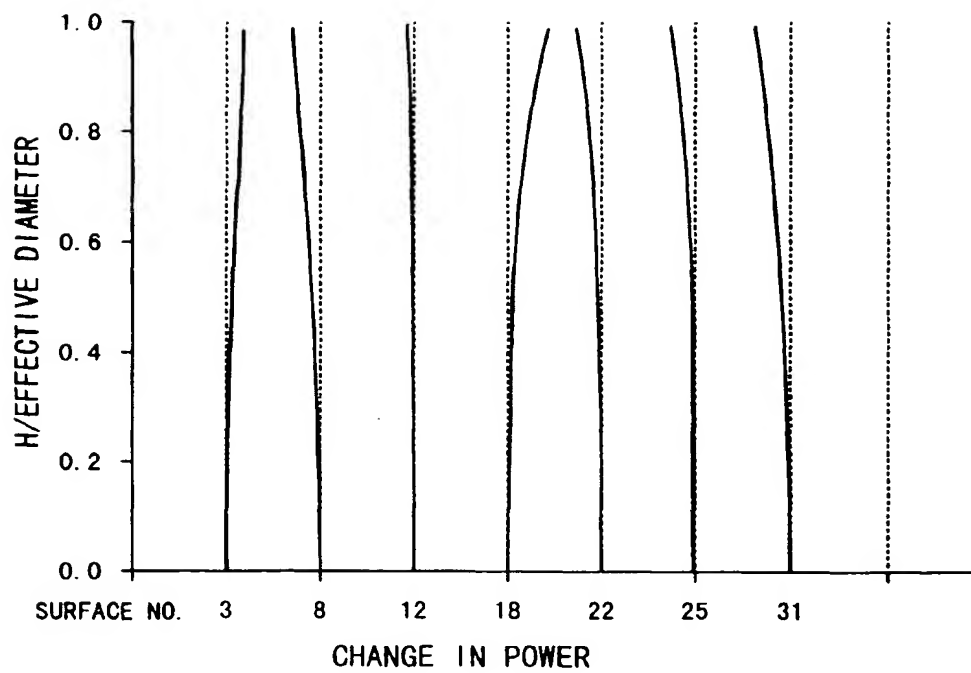


FIG. 26

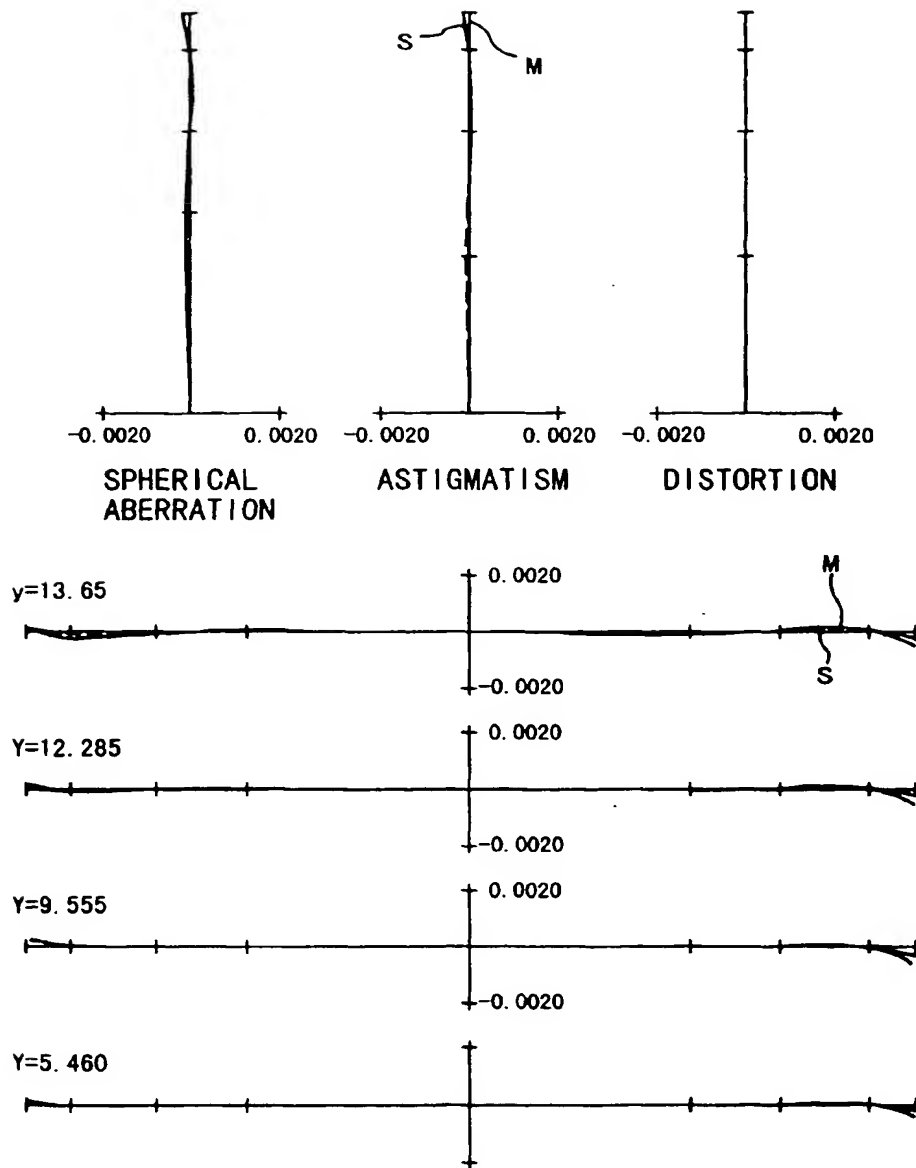


FIG. 27

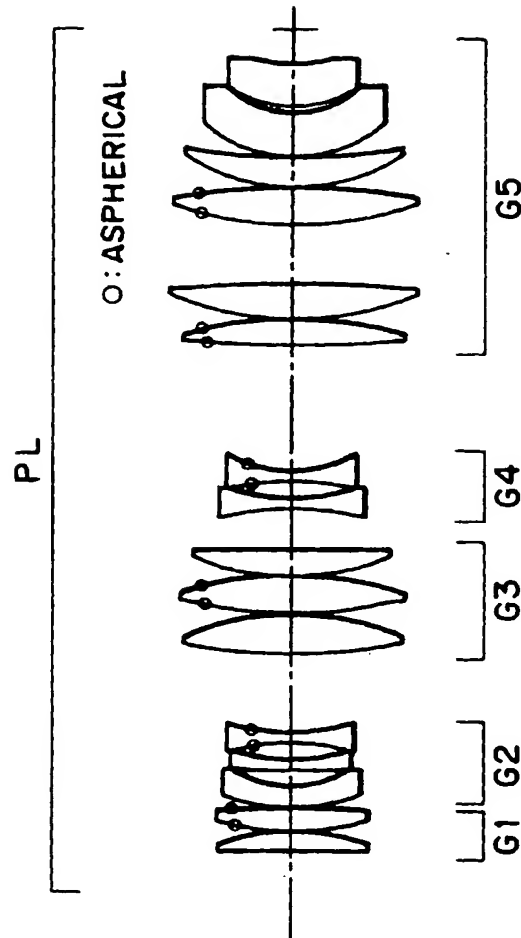


FIG. 28

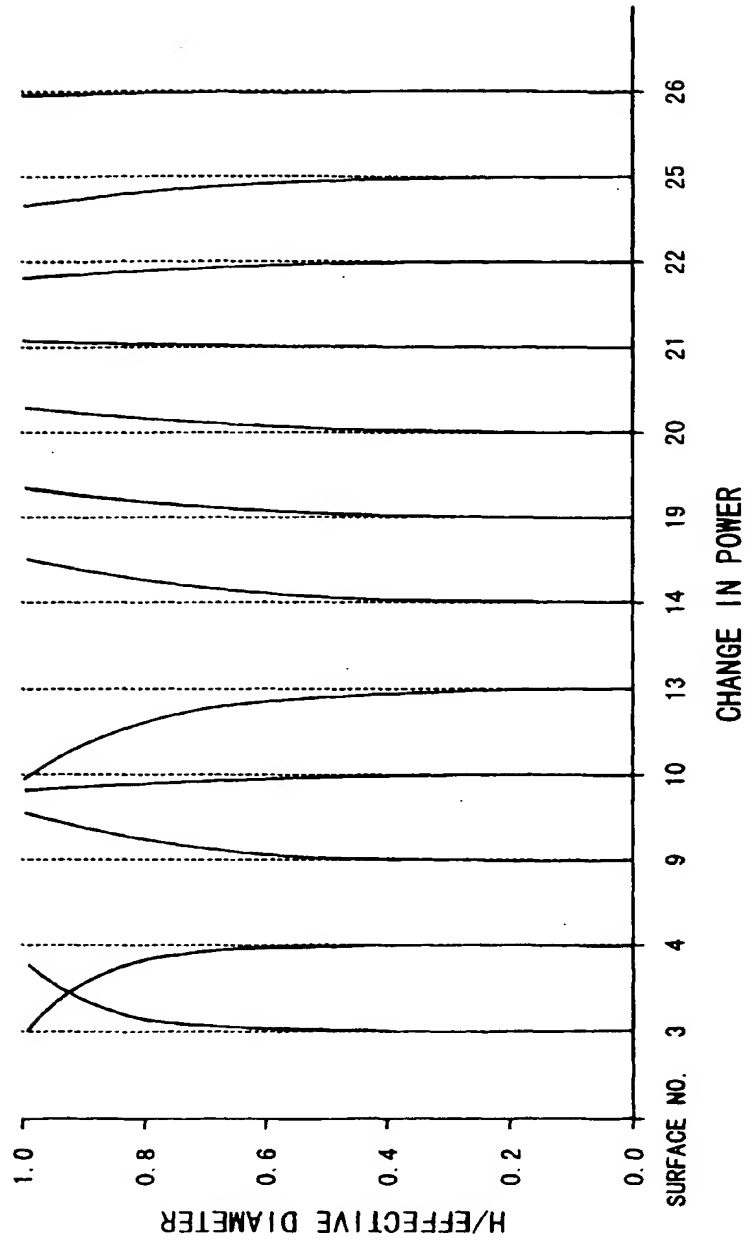


FIG. 29

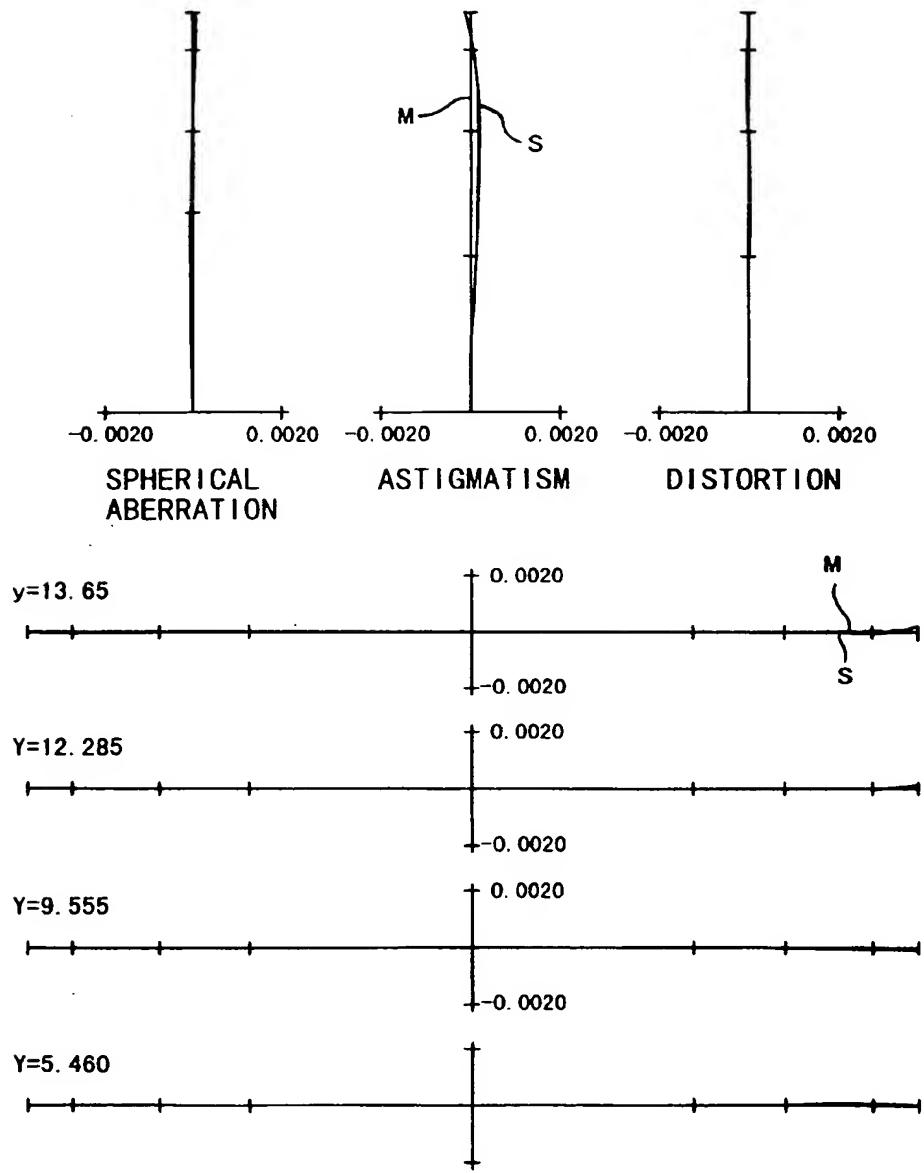


FIG. 30

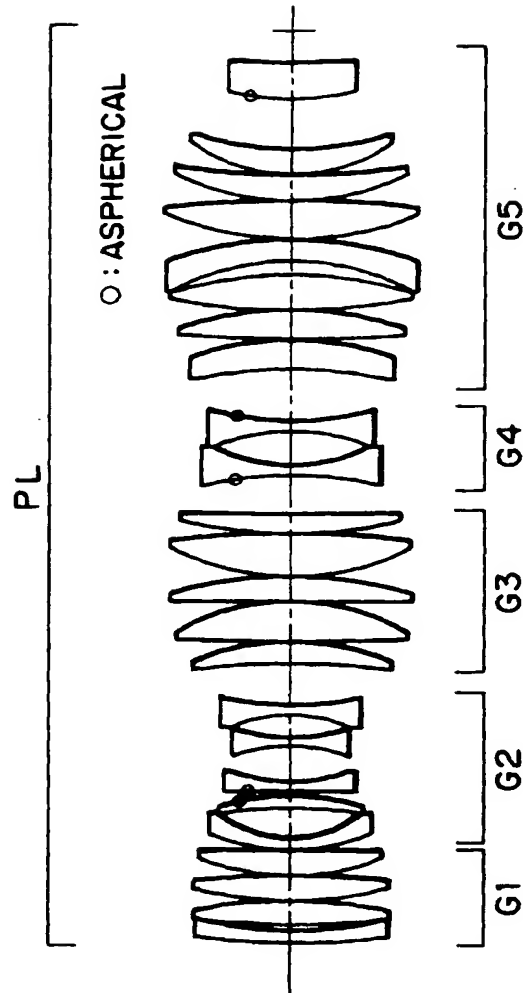


FIG. 31

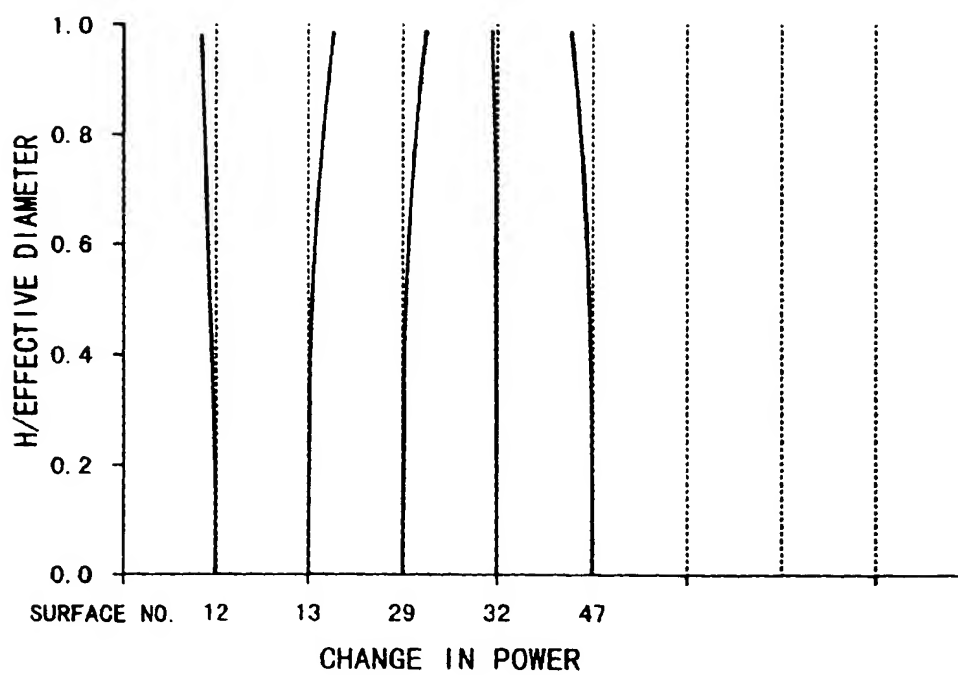


FIG. 32

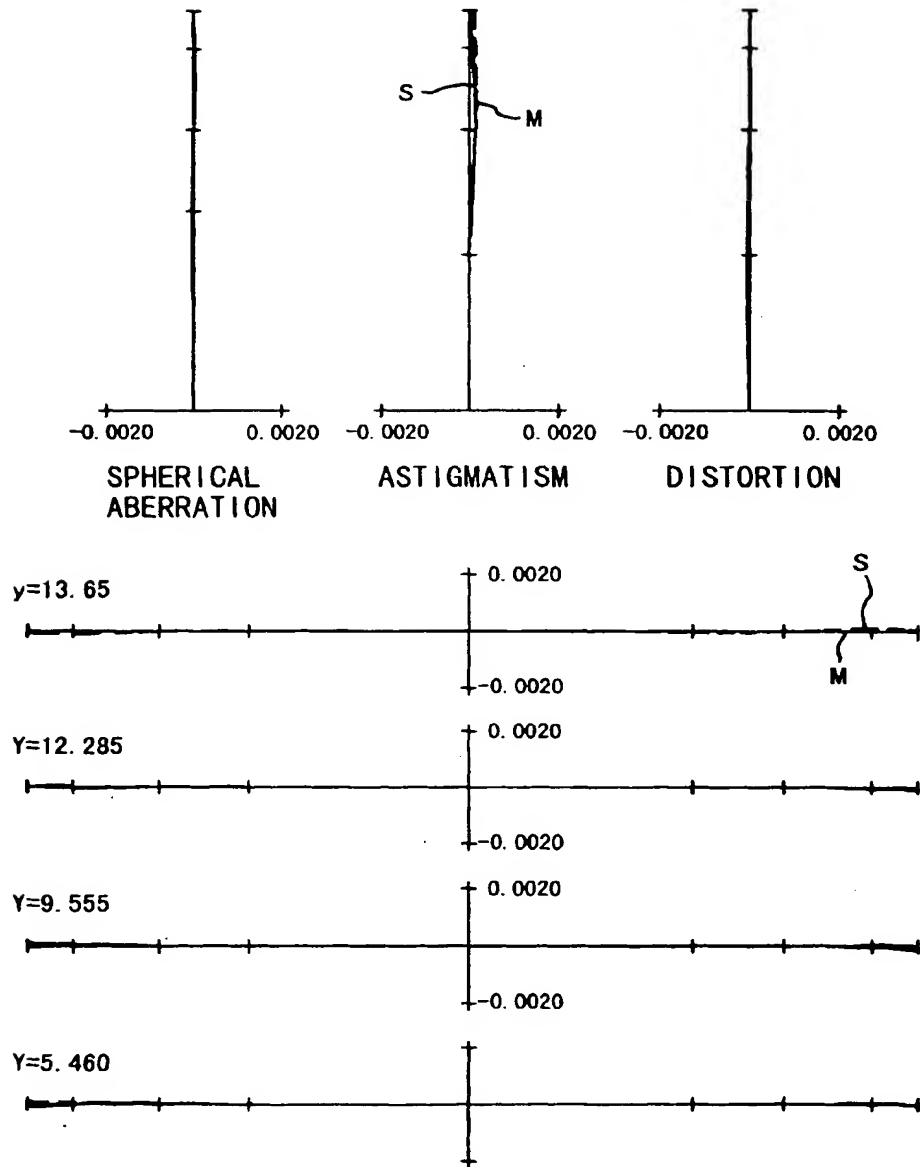


FIG. 33

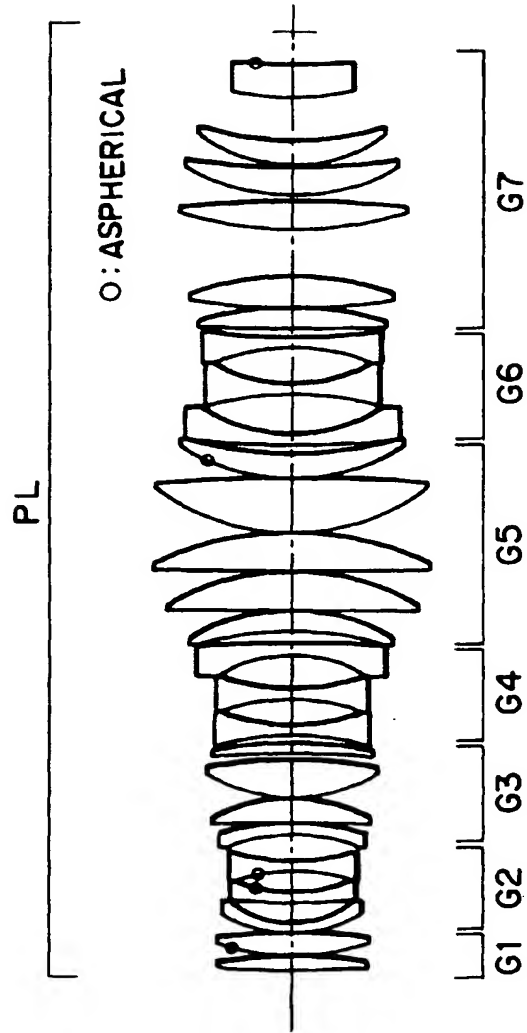


FIG. 34

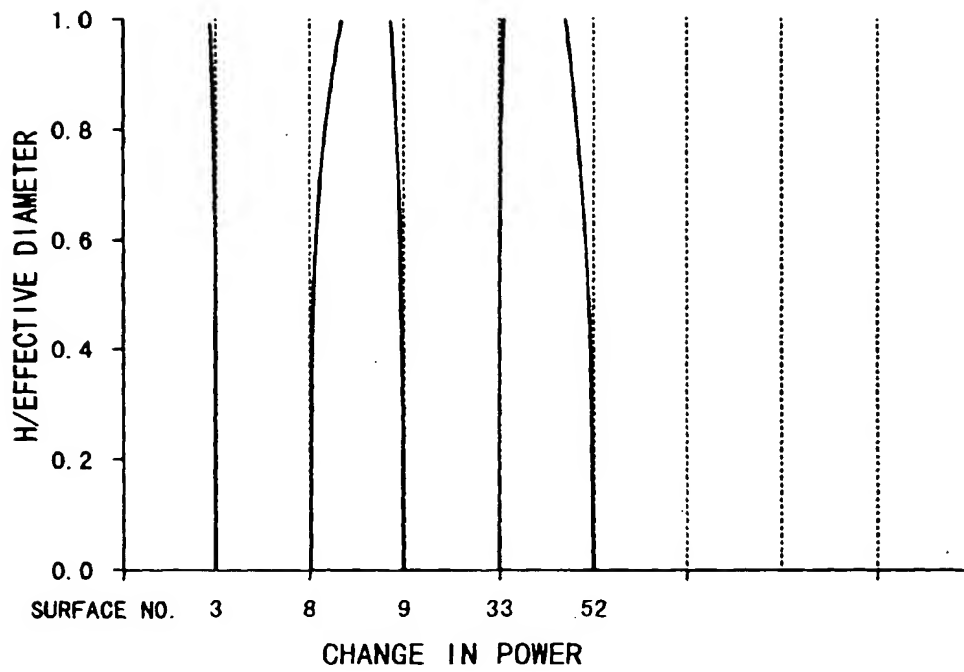


FIG. 35

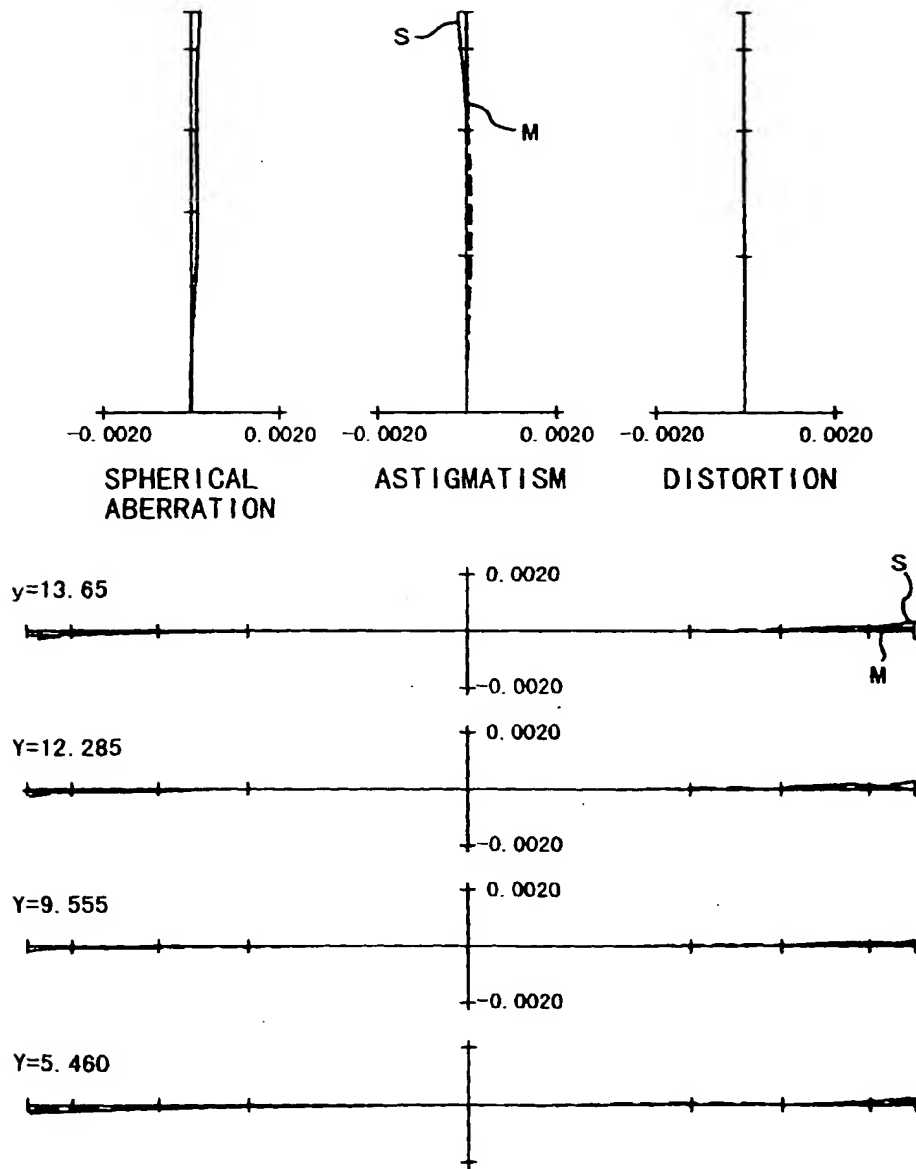


FIG. 36

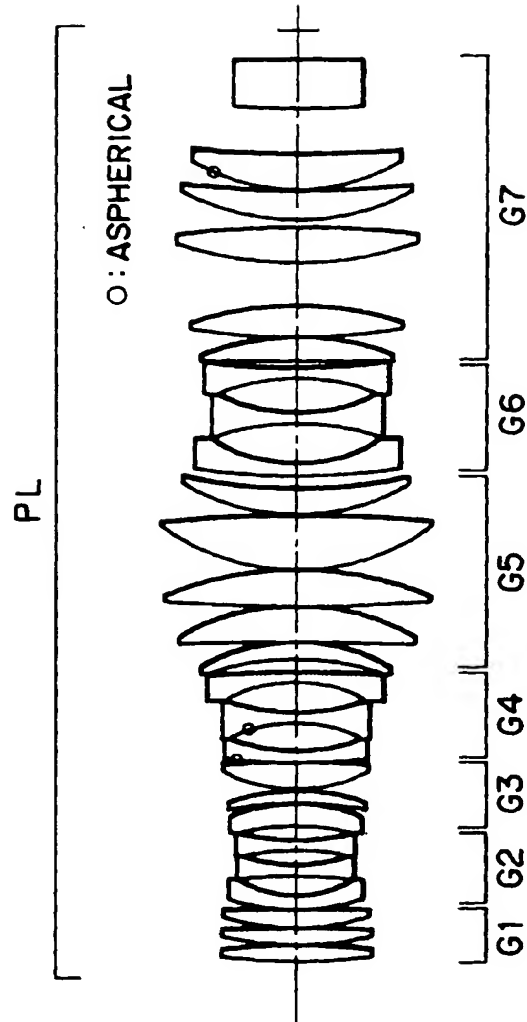


FIG. 37

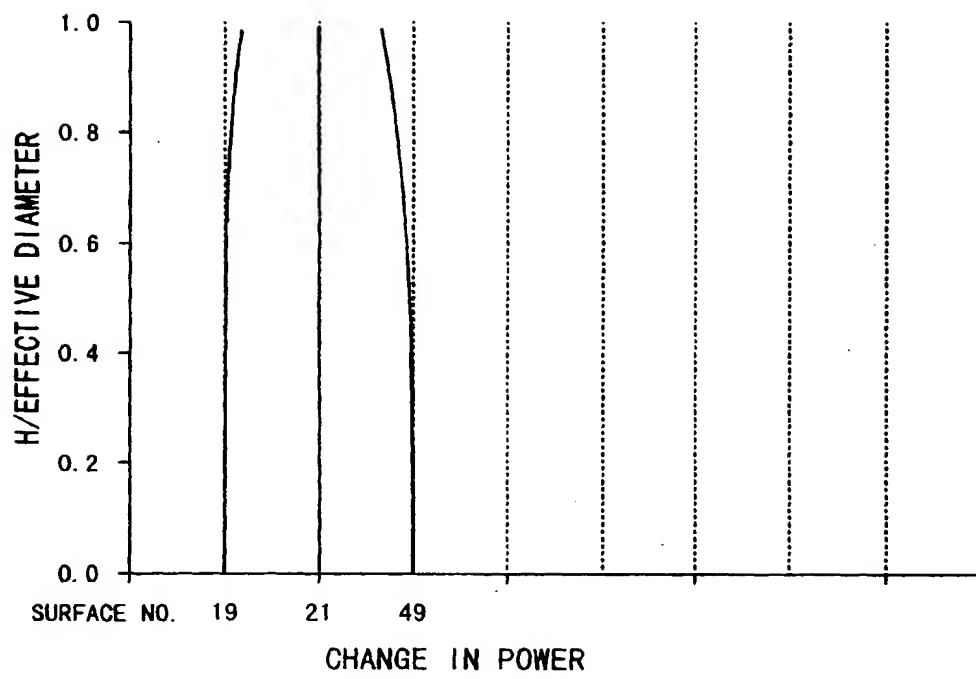


FIG. 38

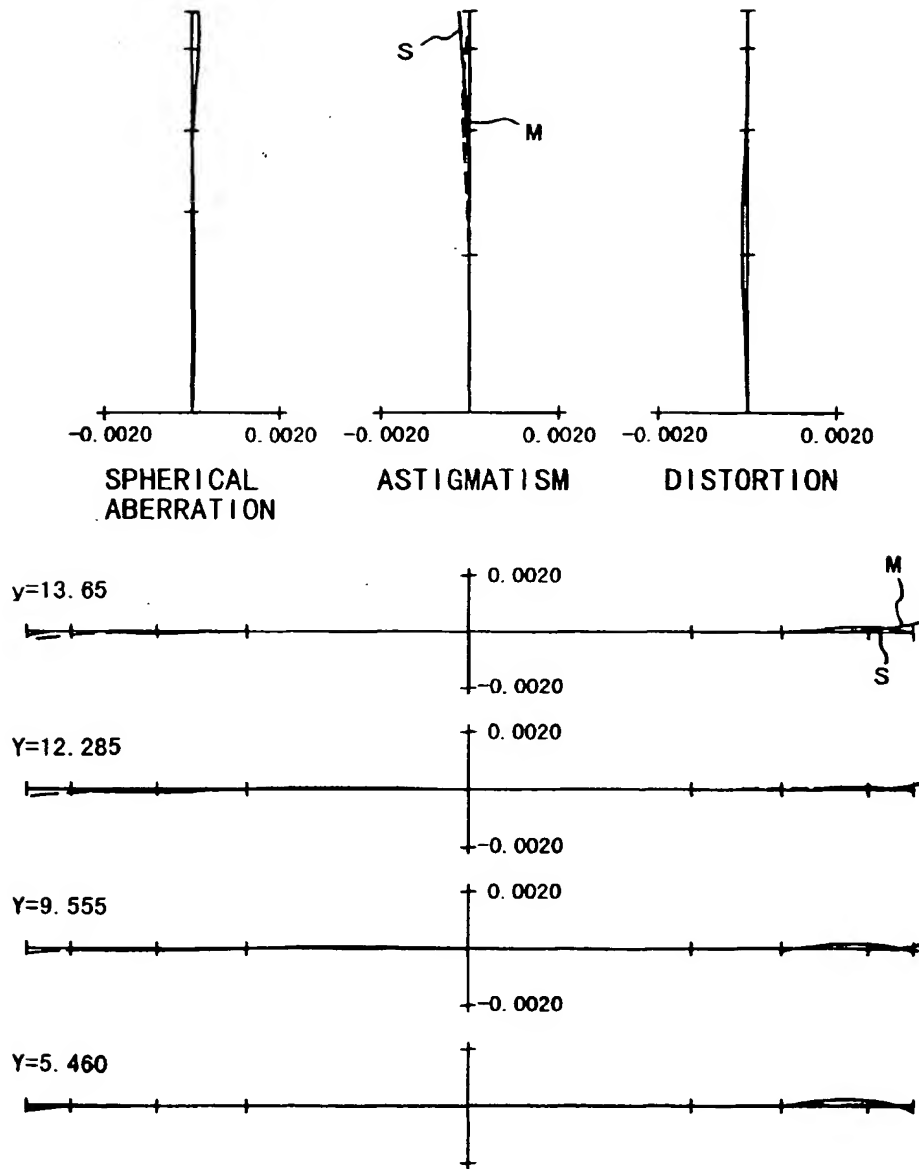


FIG. 39

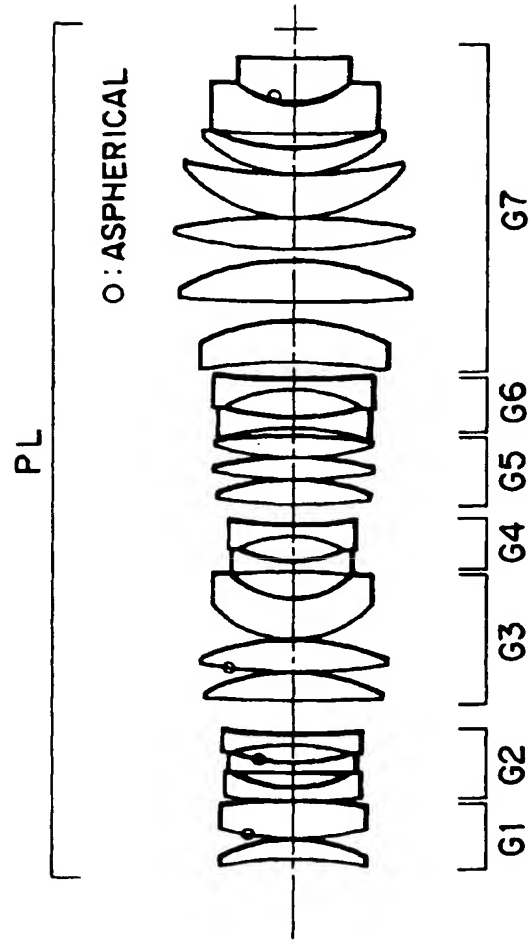


FIG. 40

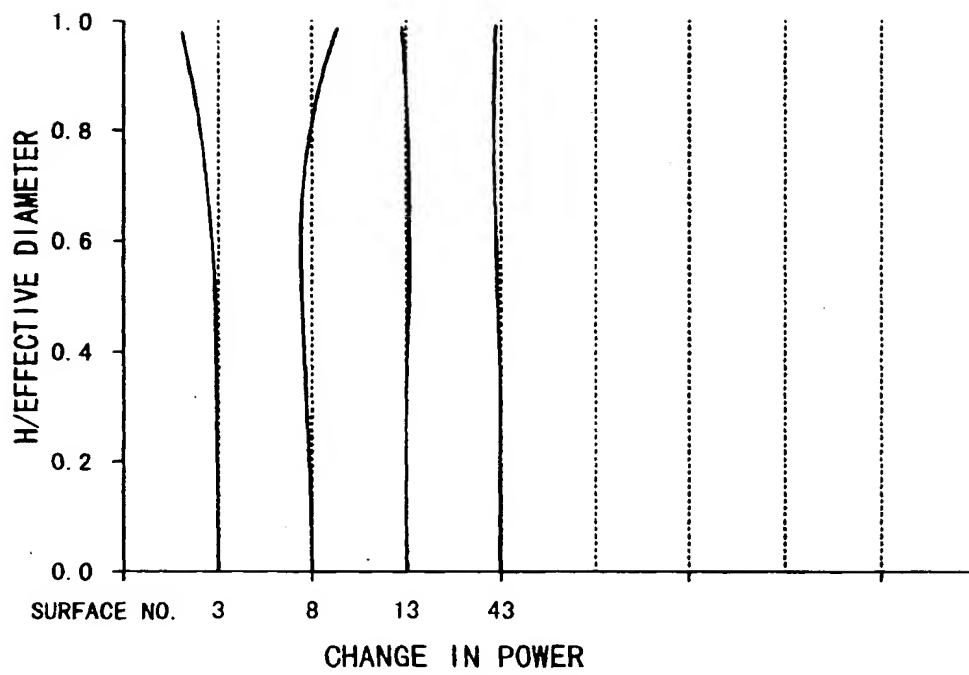


FIG. 41

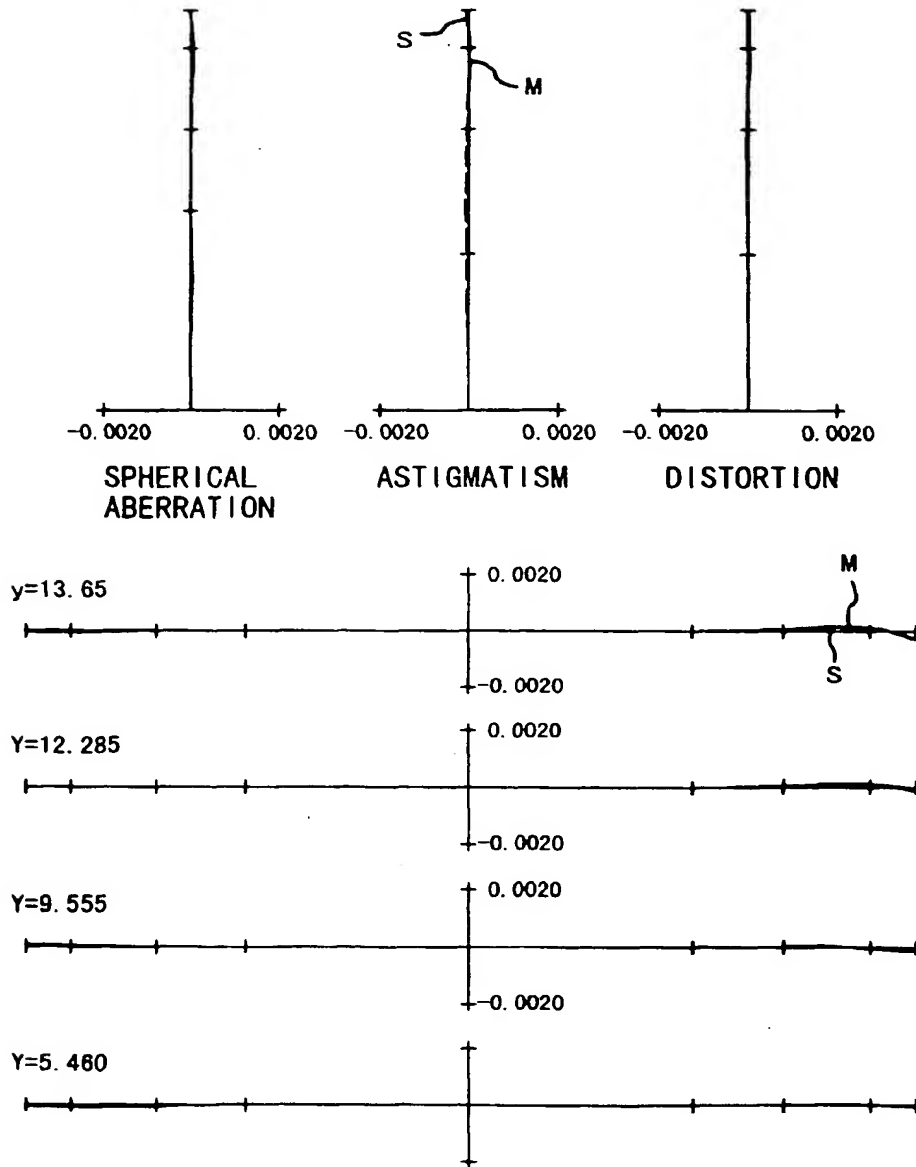


FIG. 42

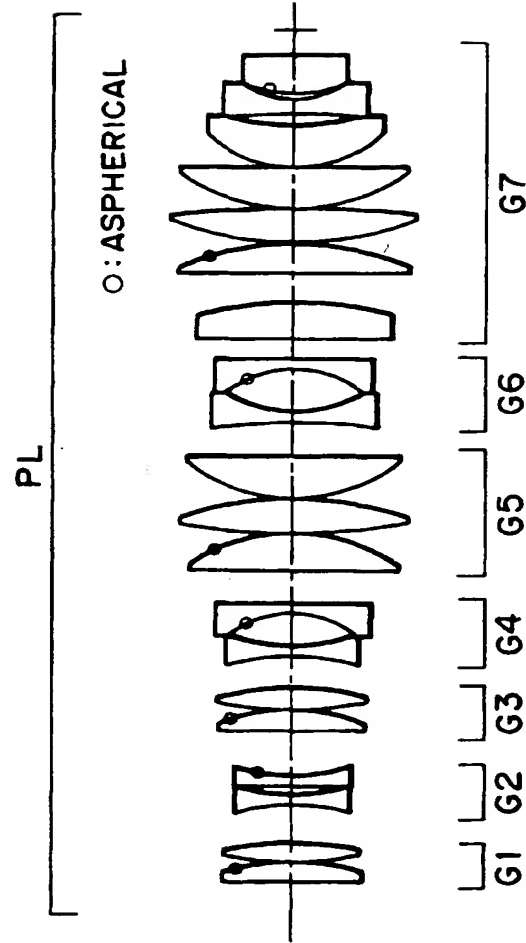


FIG. 43

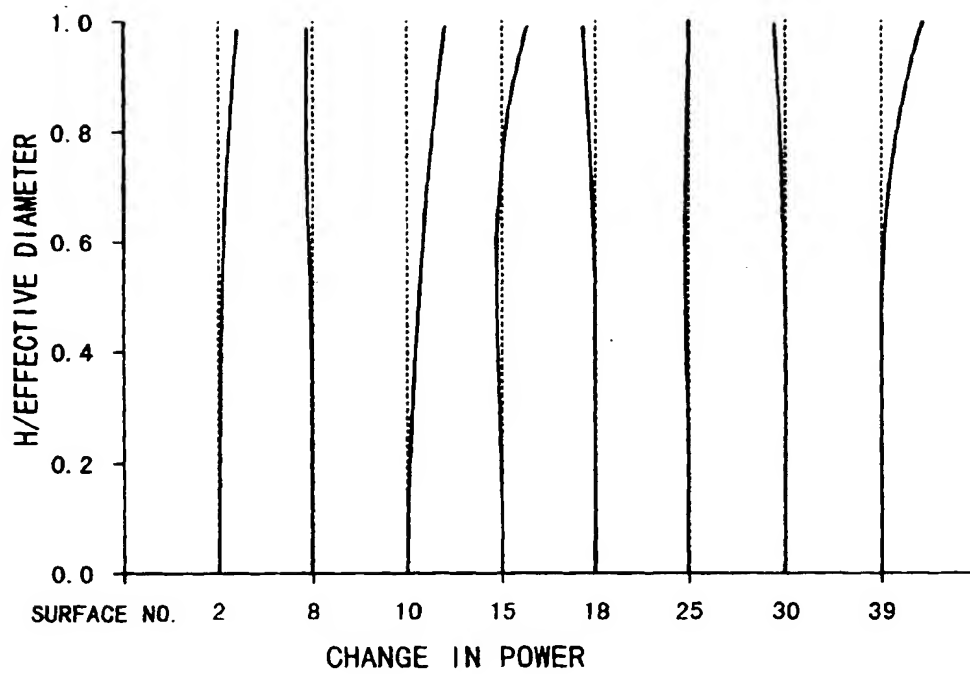


FIG. 44

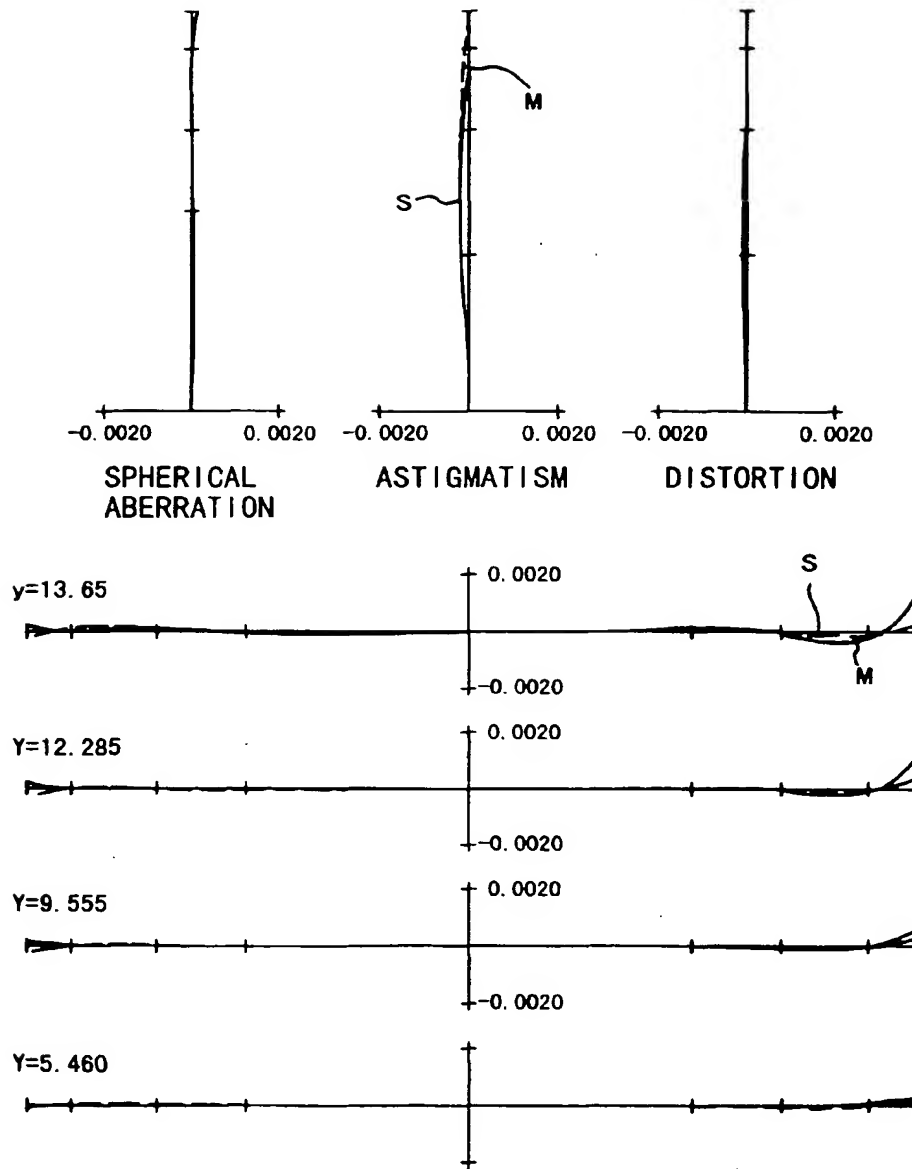


FIG. 45

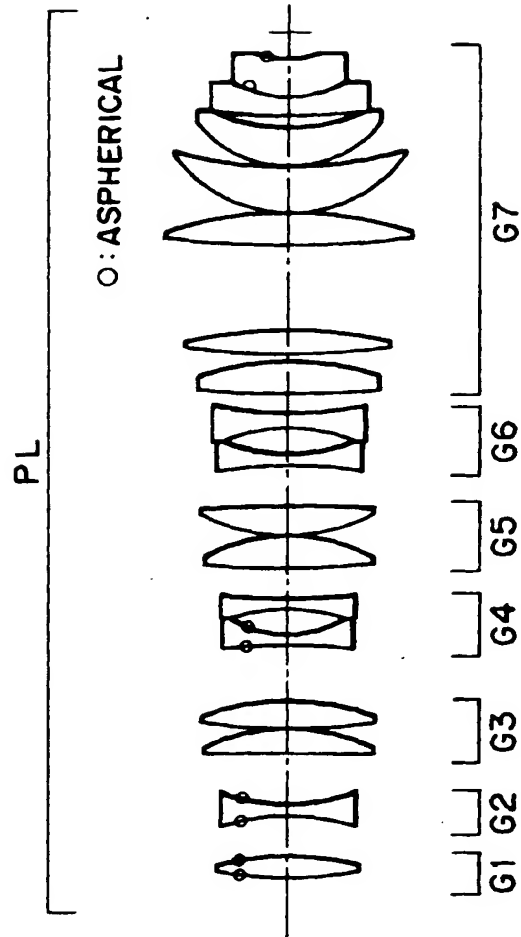


FIG. 46

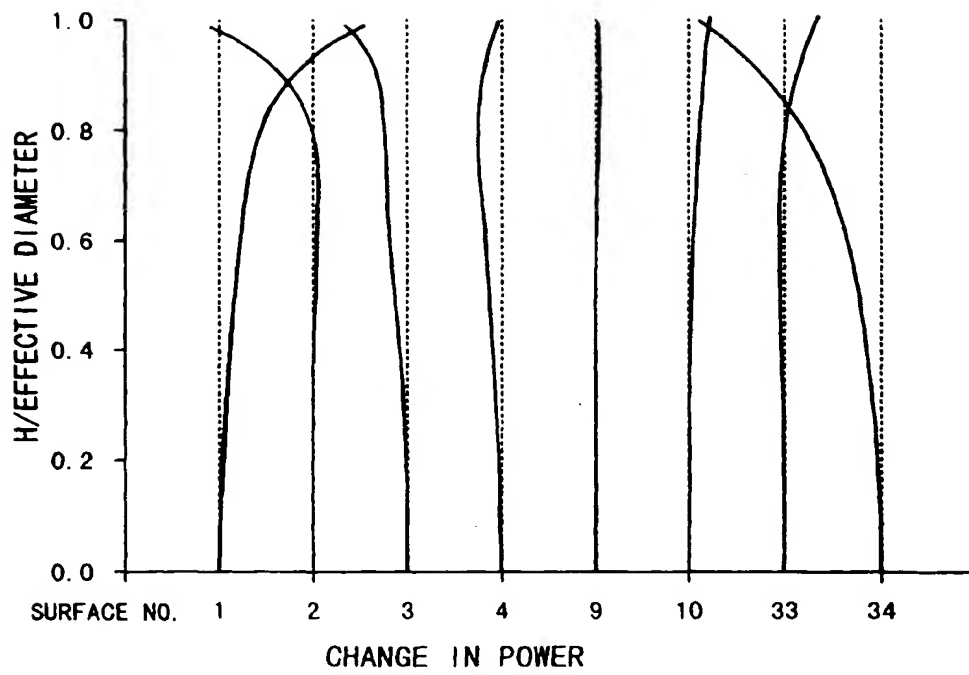


FIG. 47

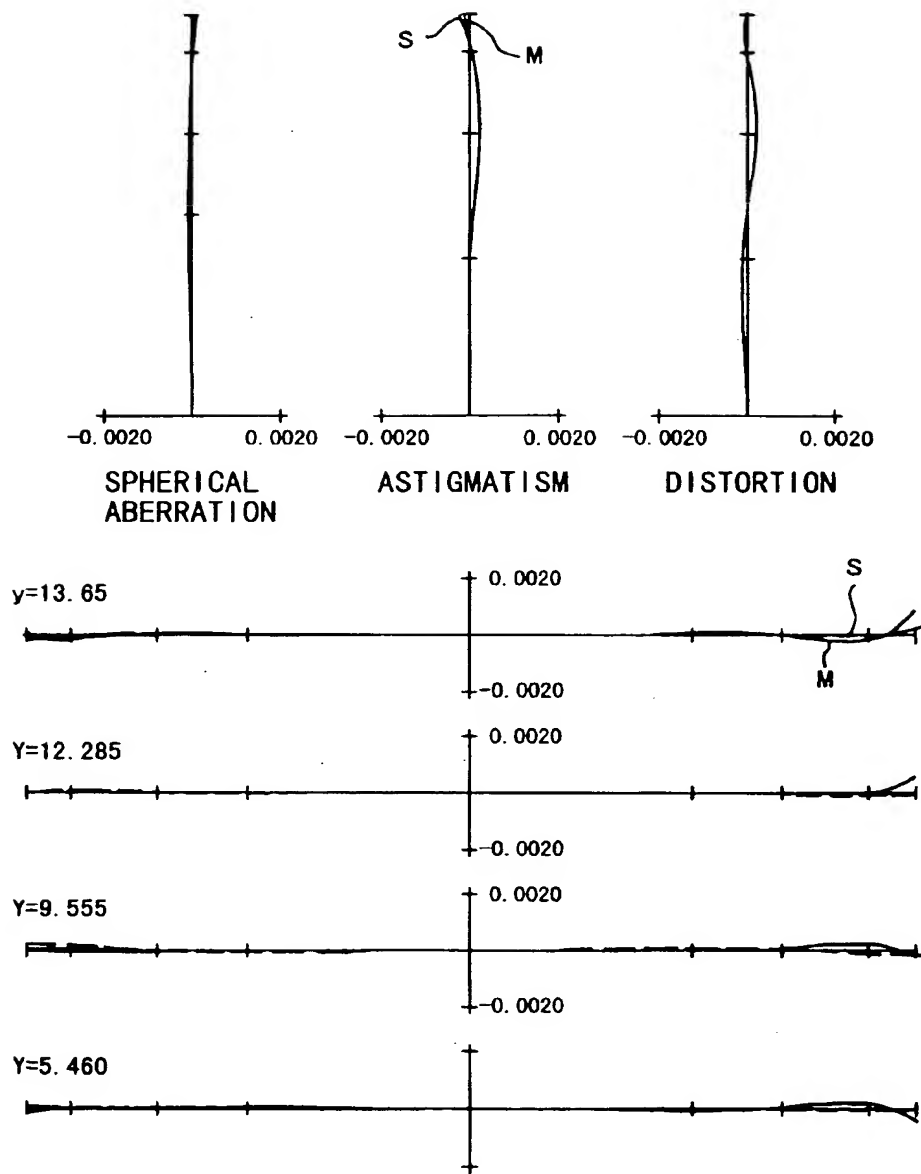


FIG. 48

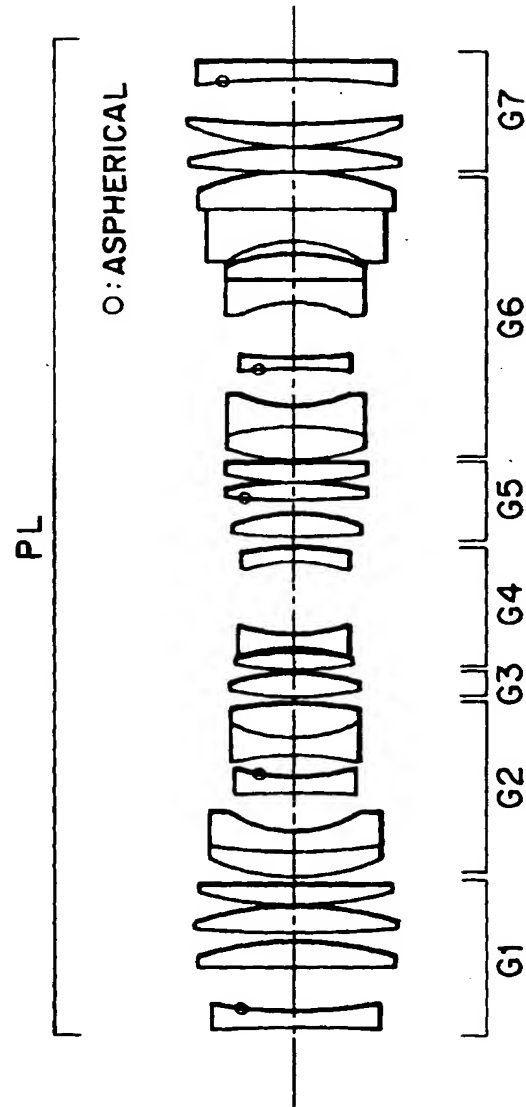


FIG. 49

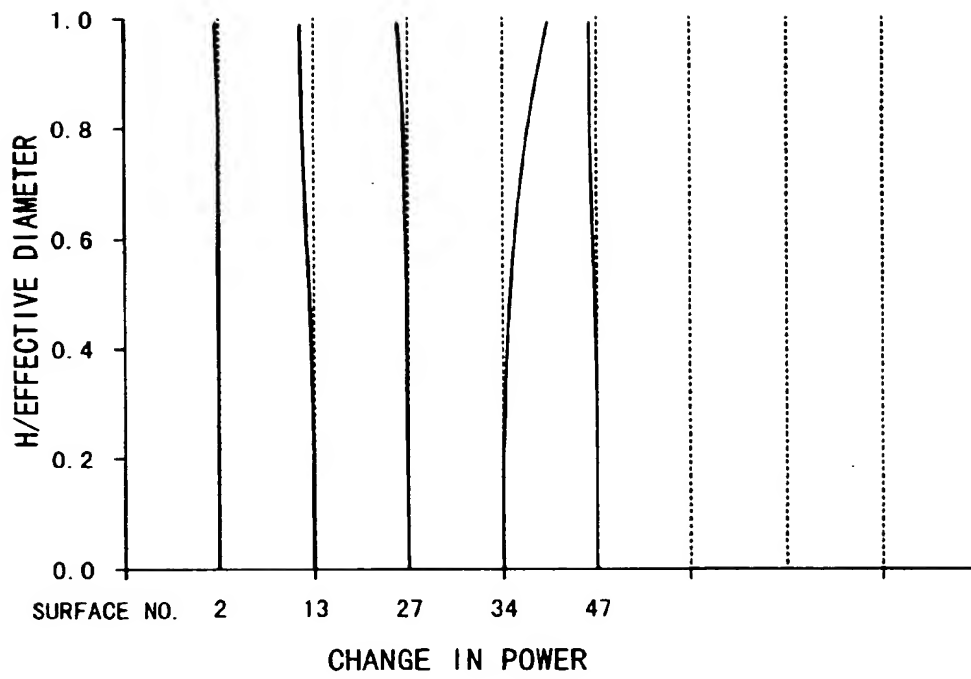


FIG. 50

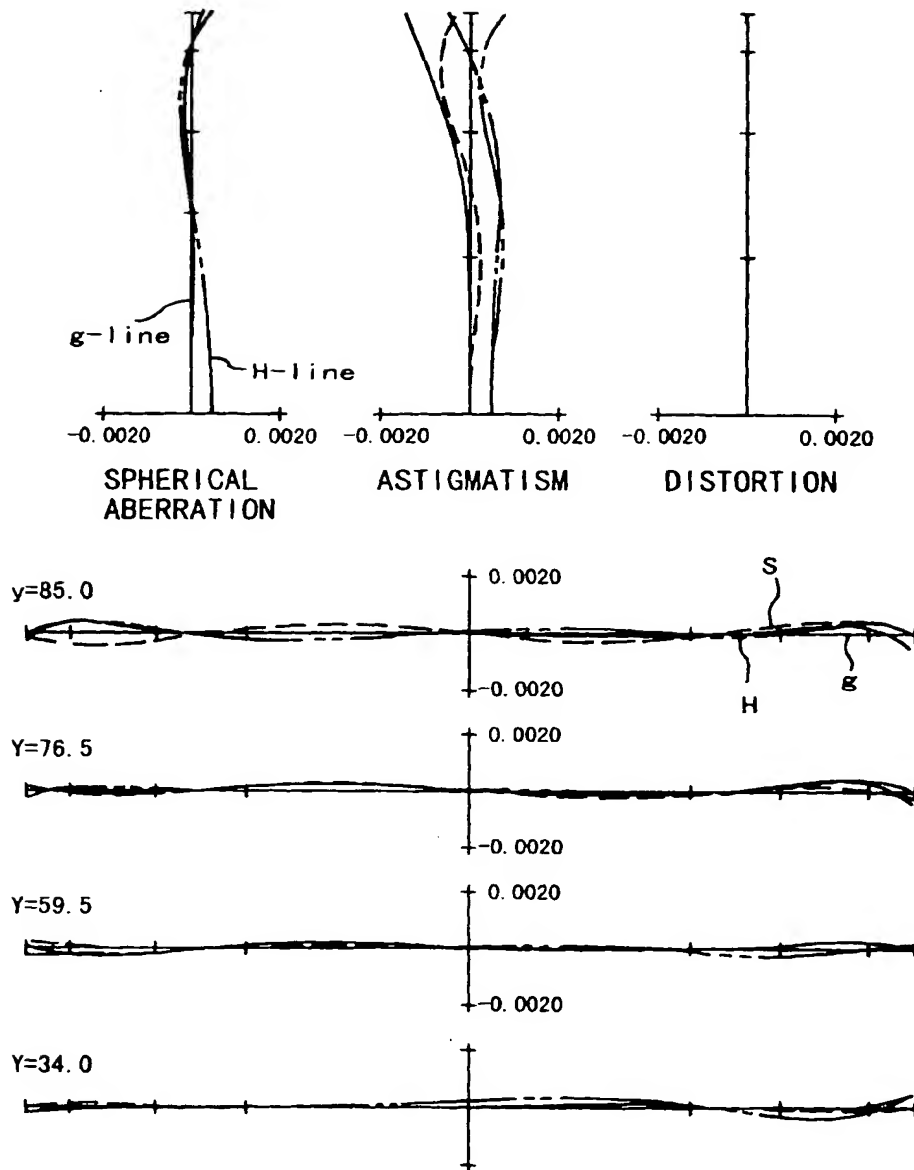


FIG. 51

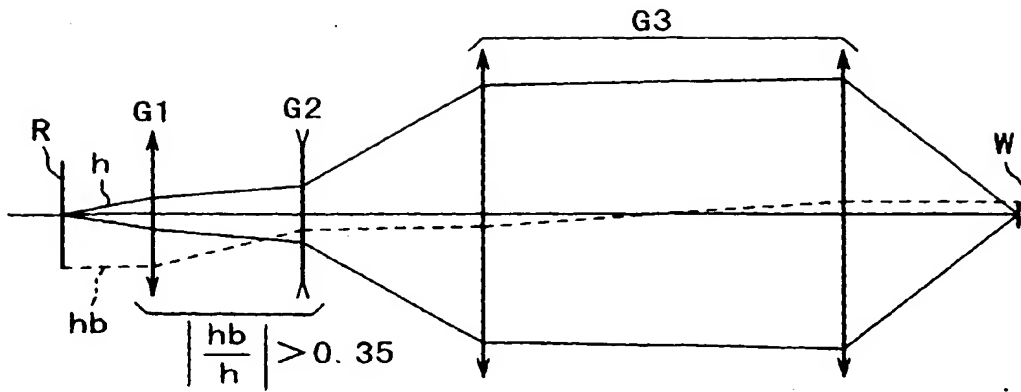


FIG. 52

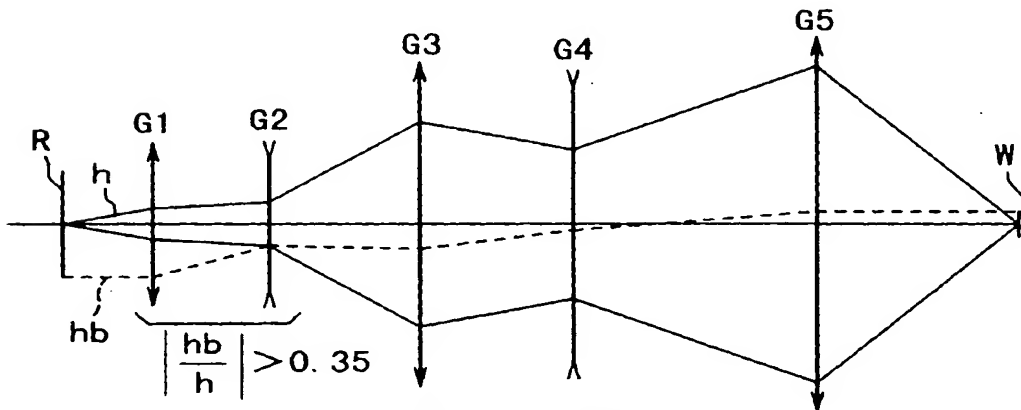


FIG. 53

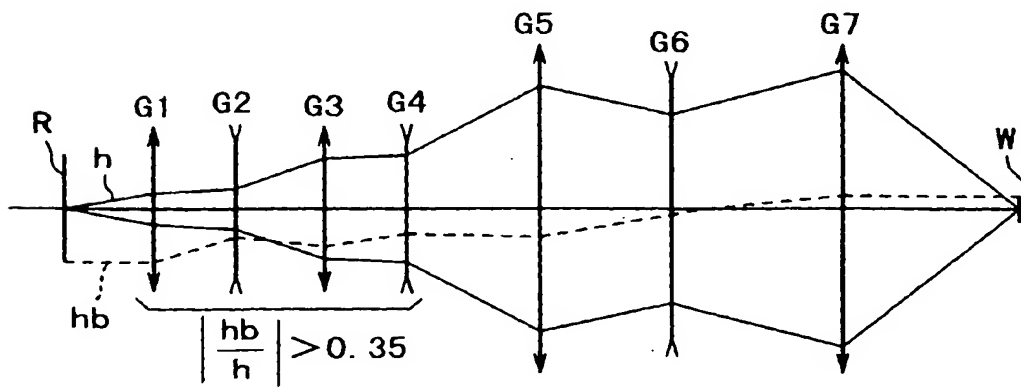


FIG. 54

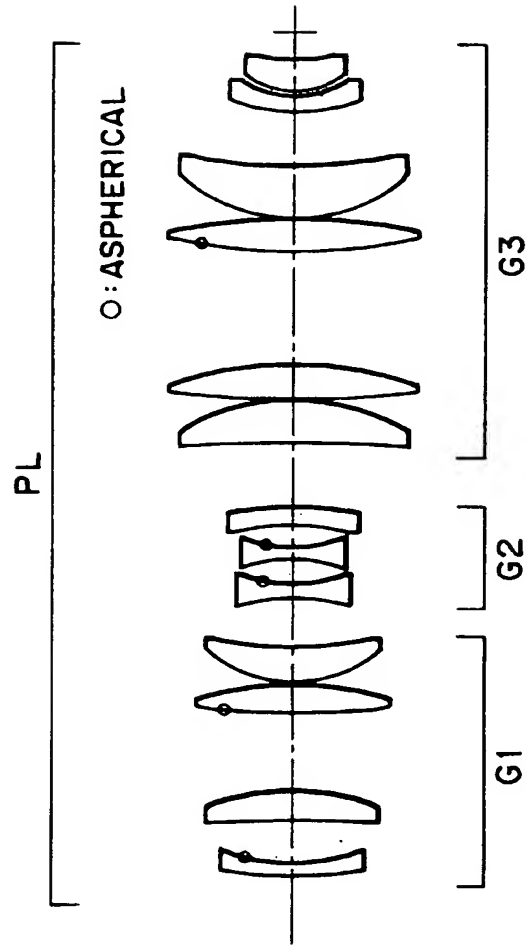


FIG. 55

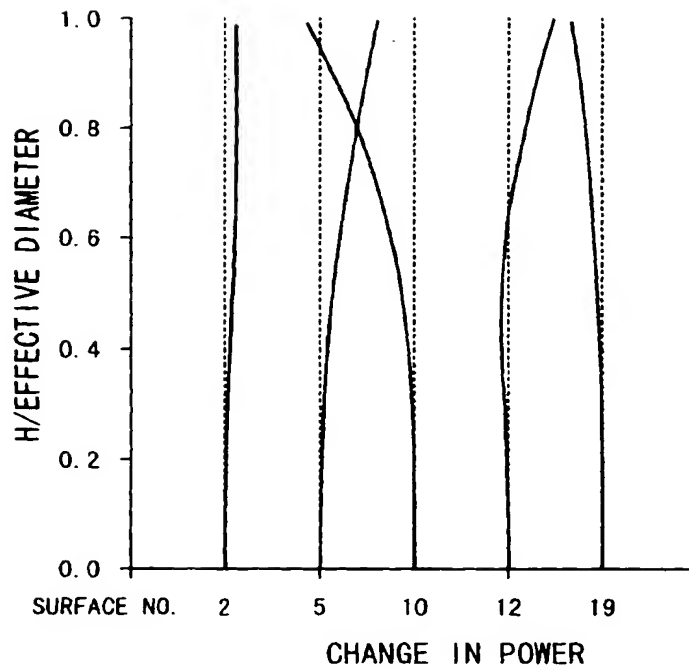


FIG. 56

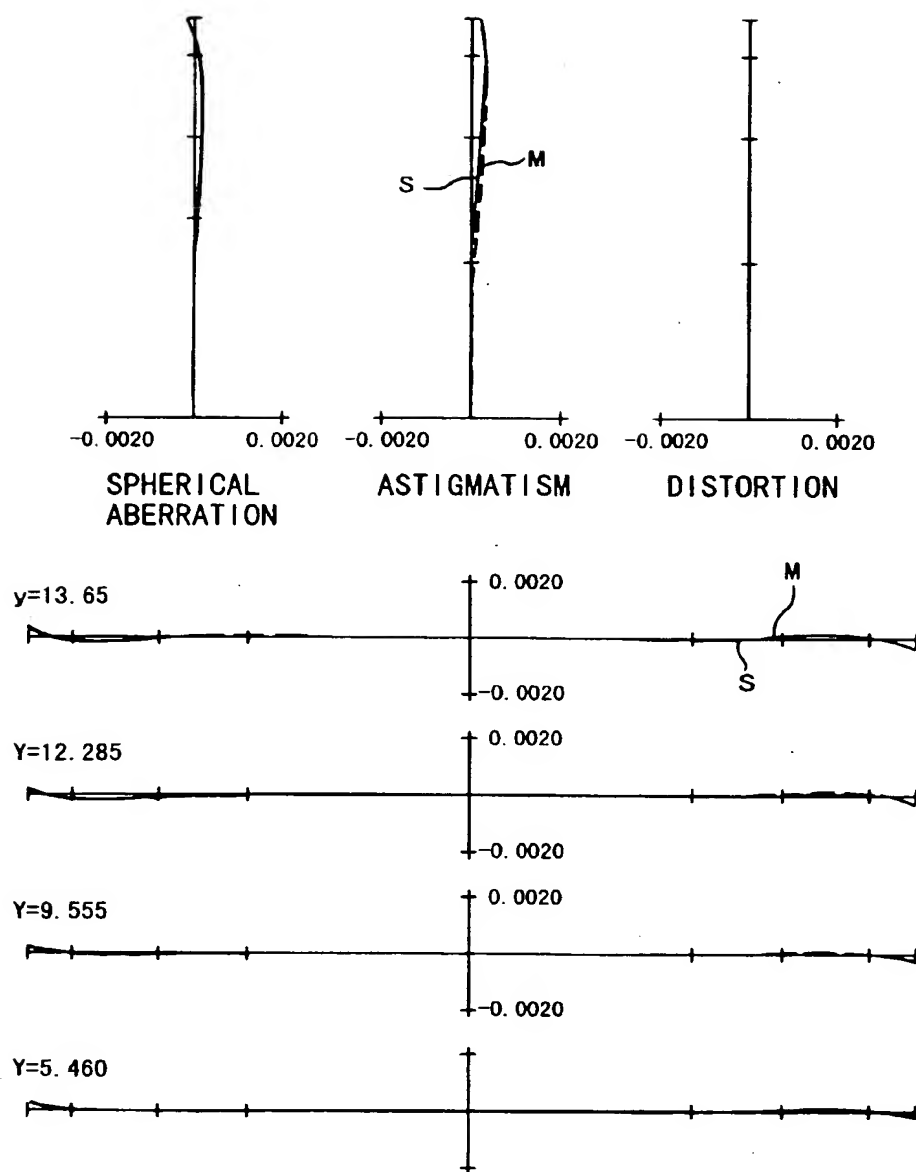


FIG. 57

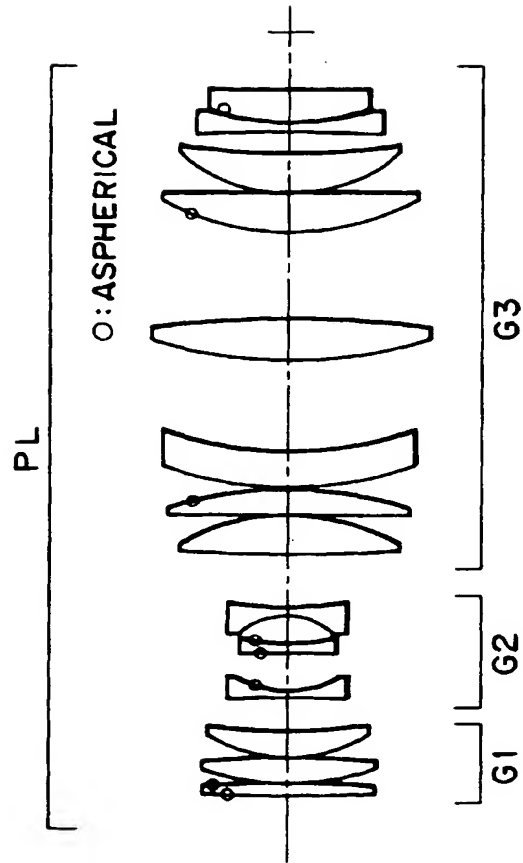


FIG. 58

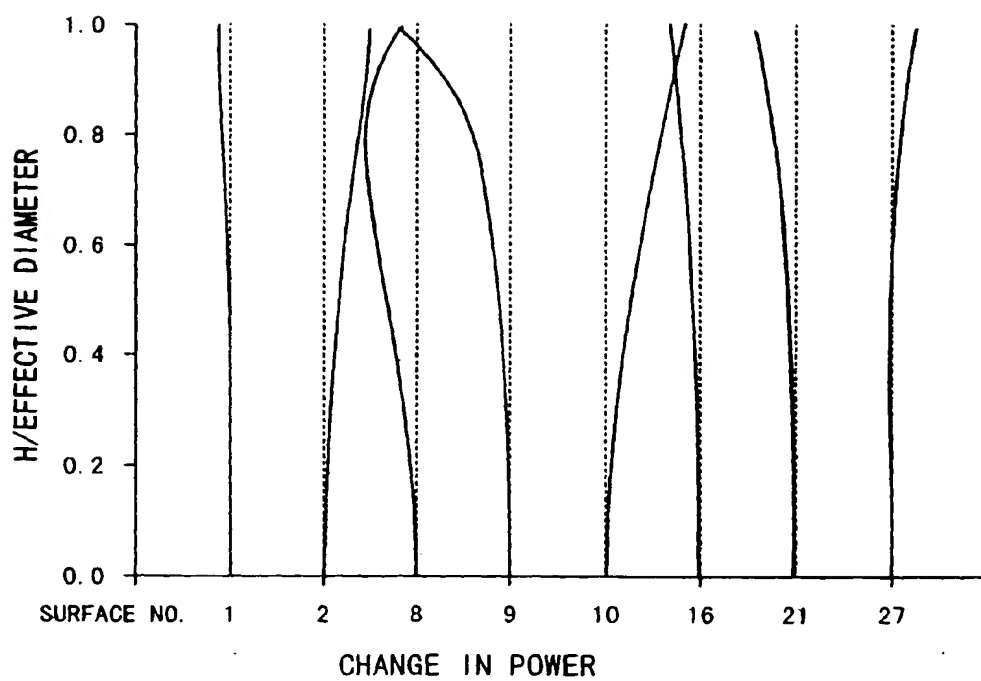


FIG. 59

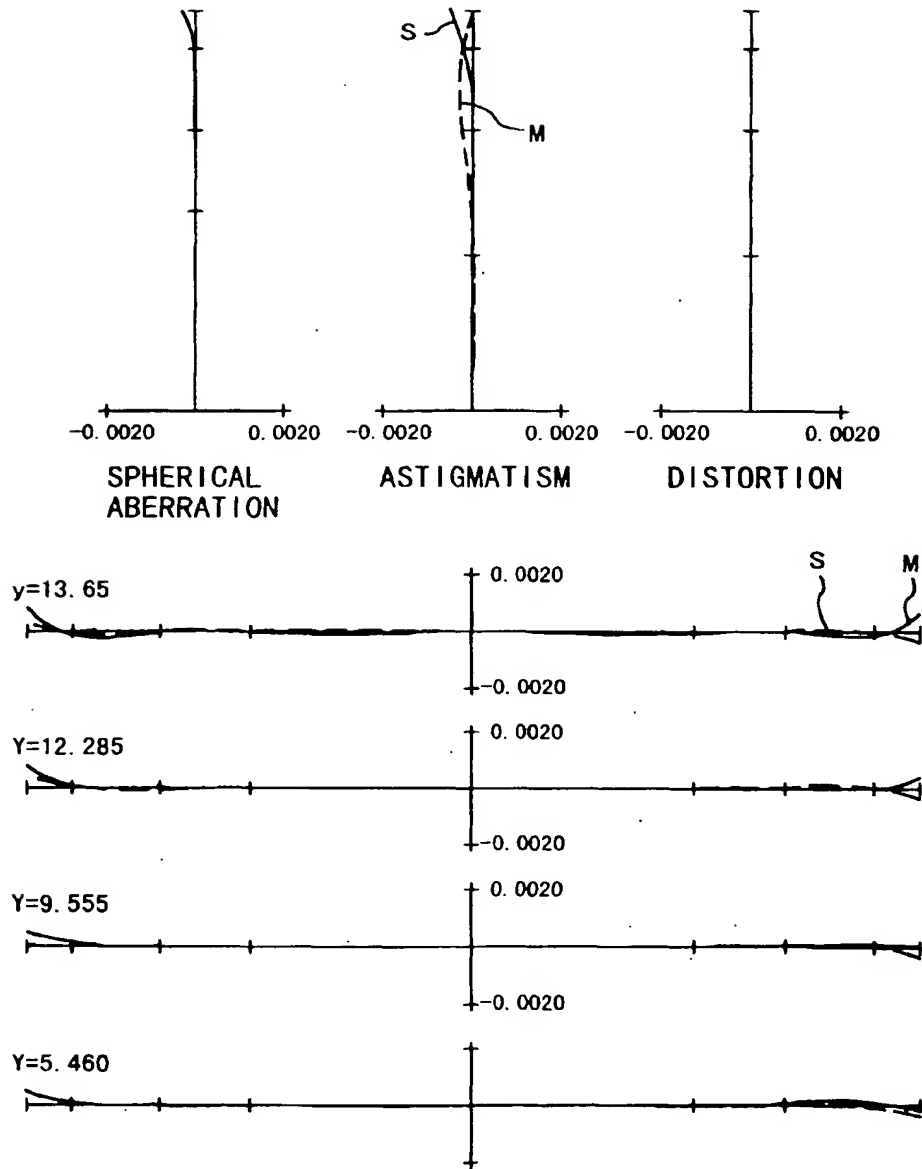


FIG. 60

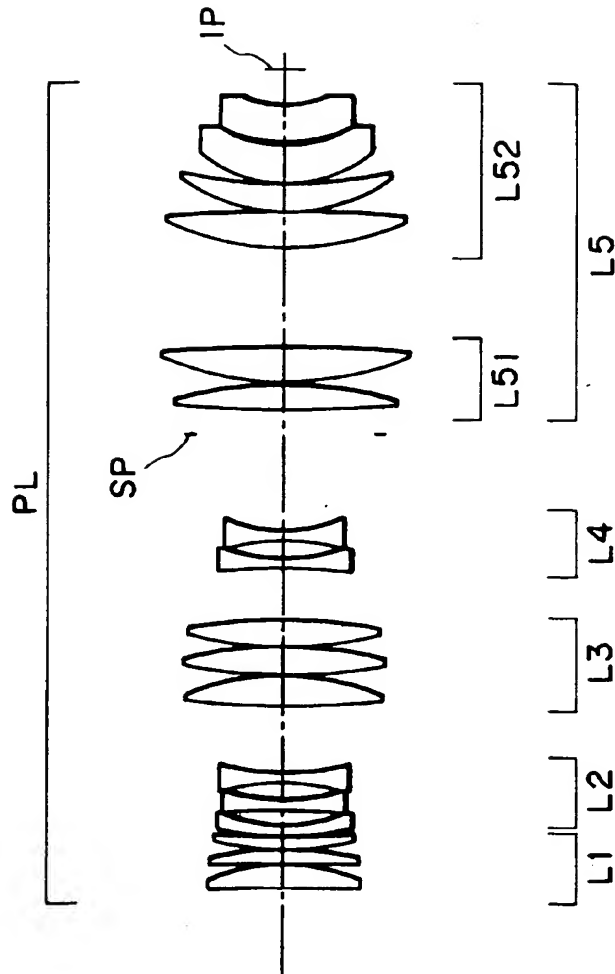


FIG. 61

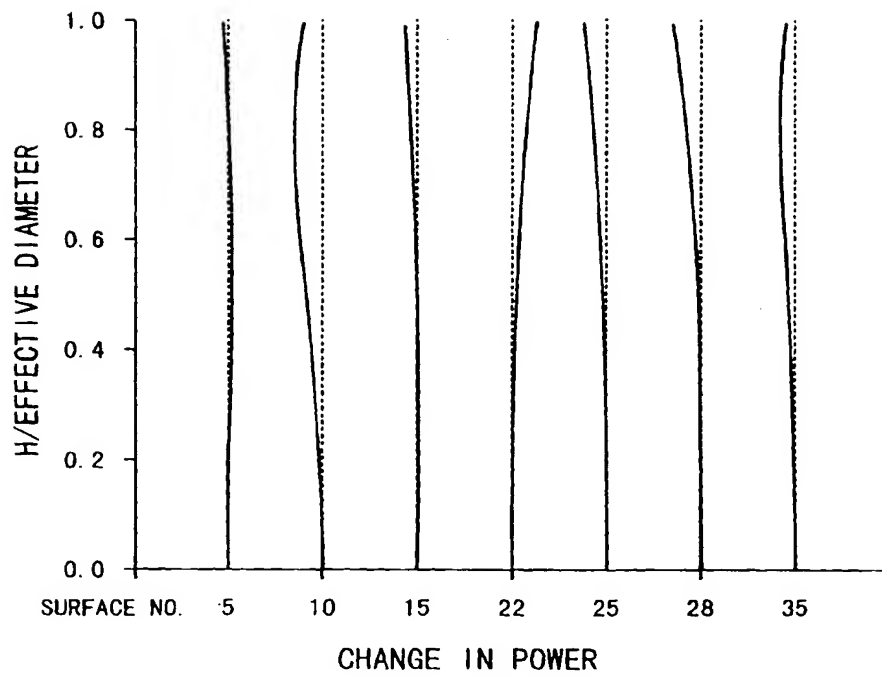


FIG. 62

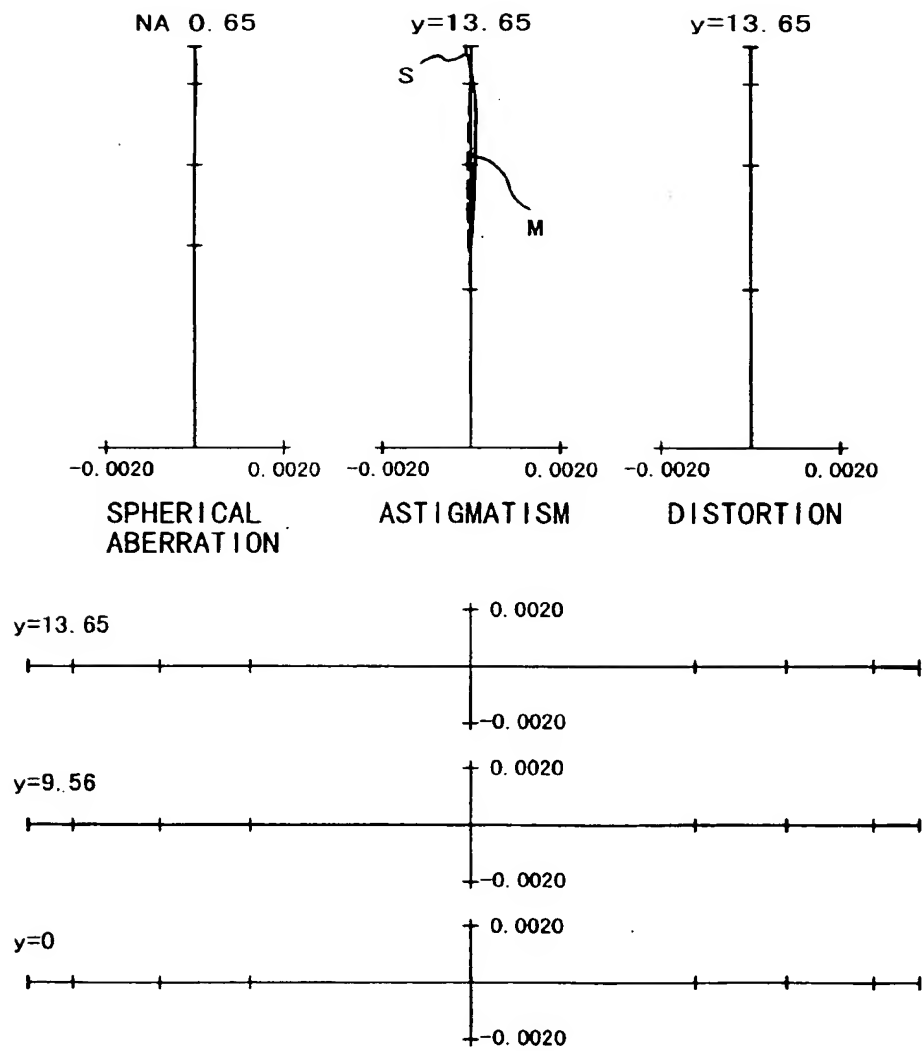


FIG. 63

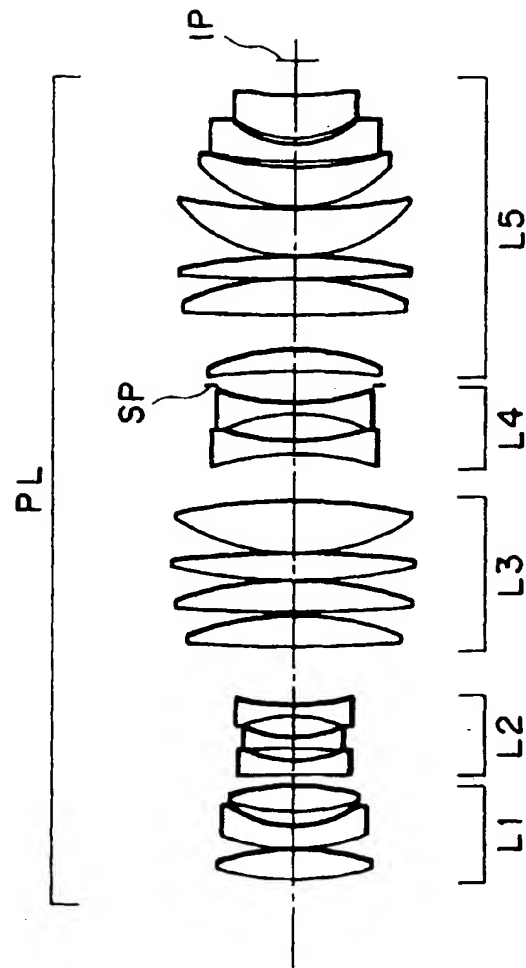


FIG. 64

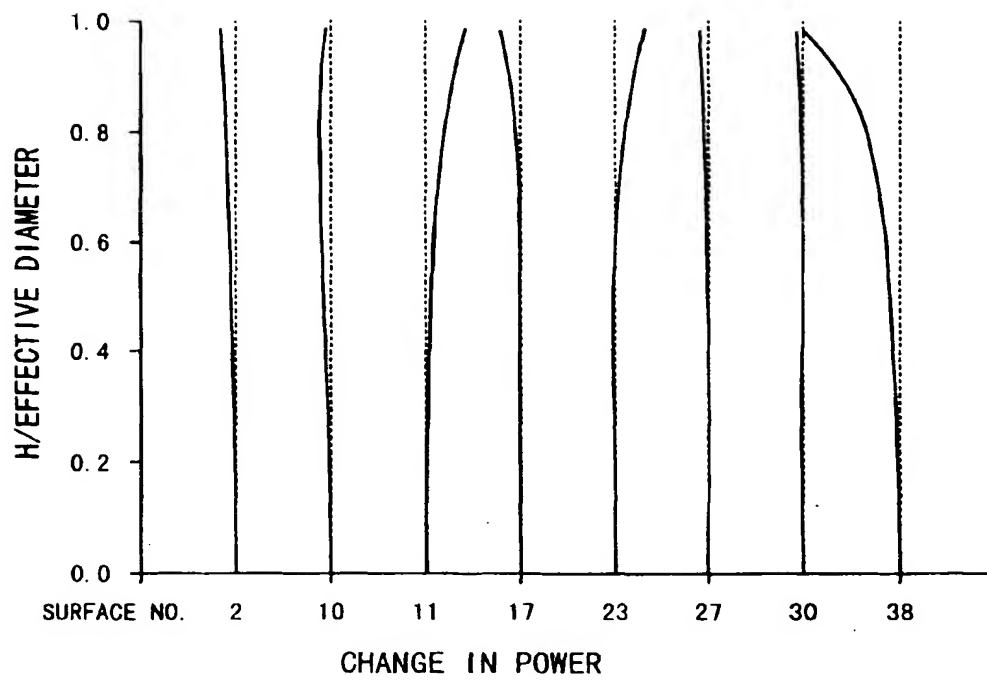


FIG. 65

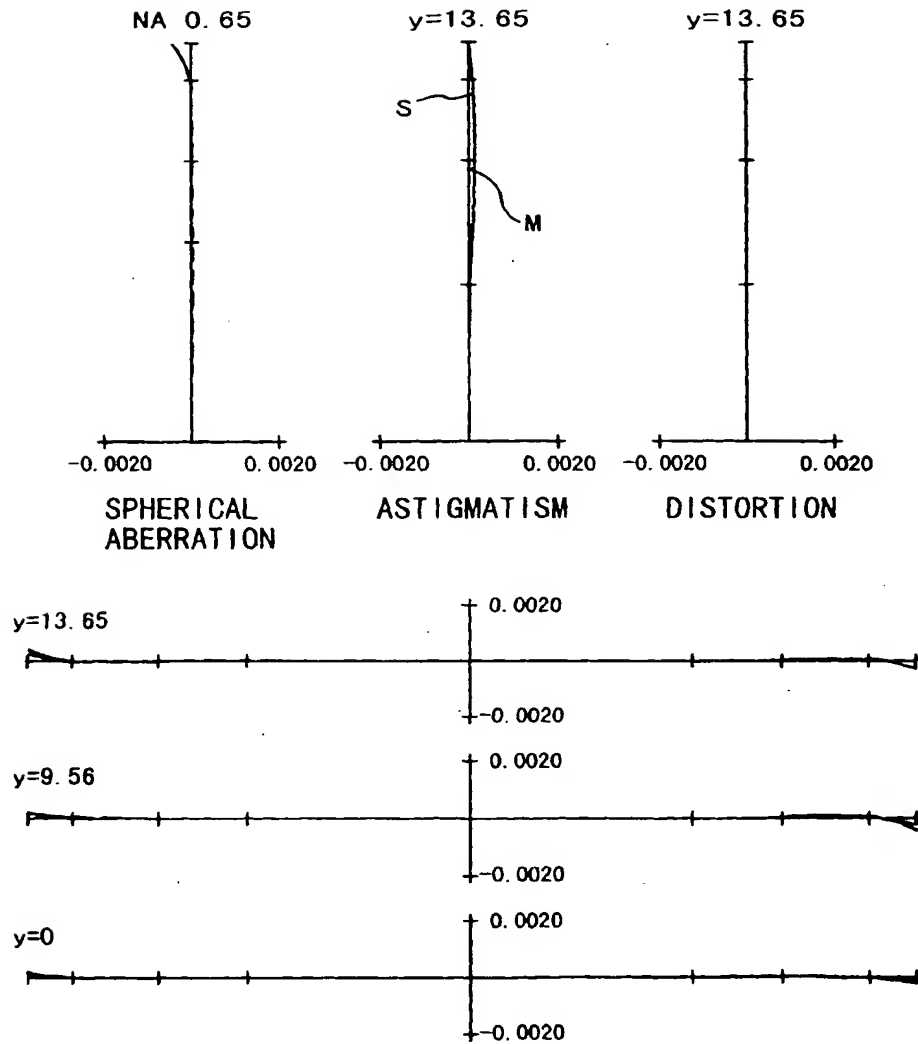


FIG. 66

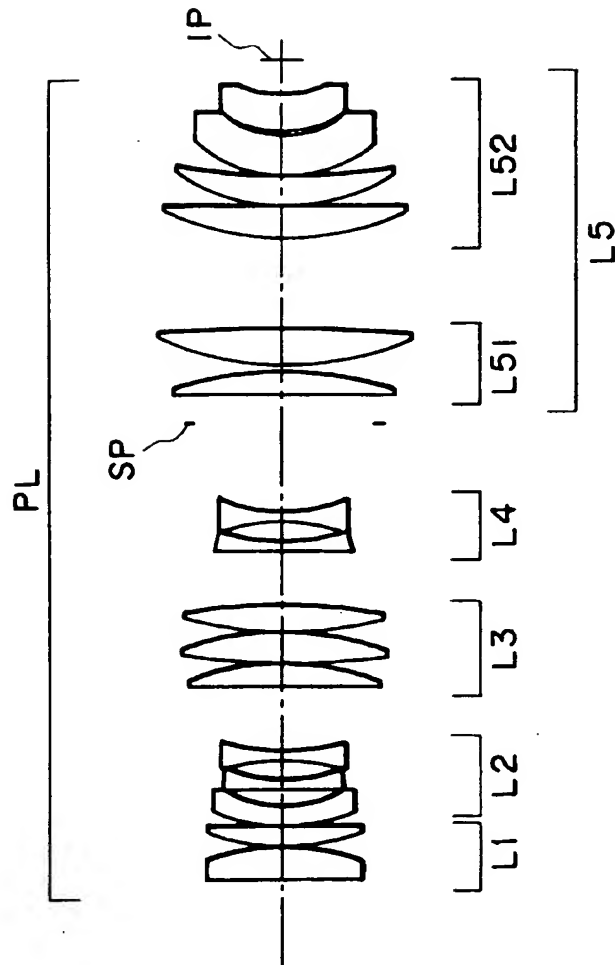


FIG. 67

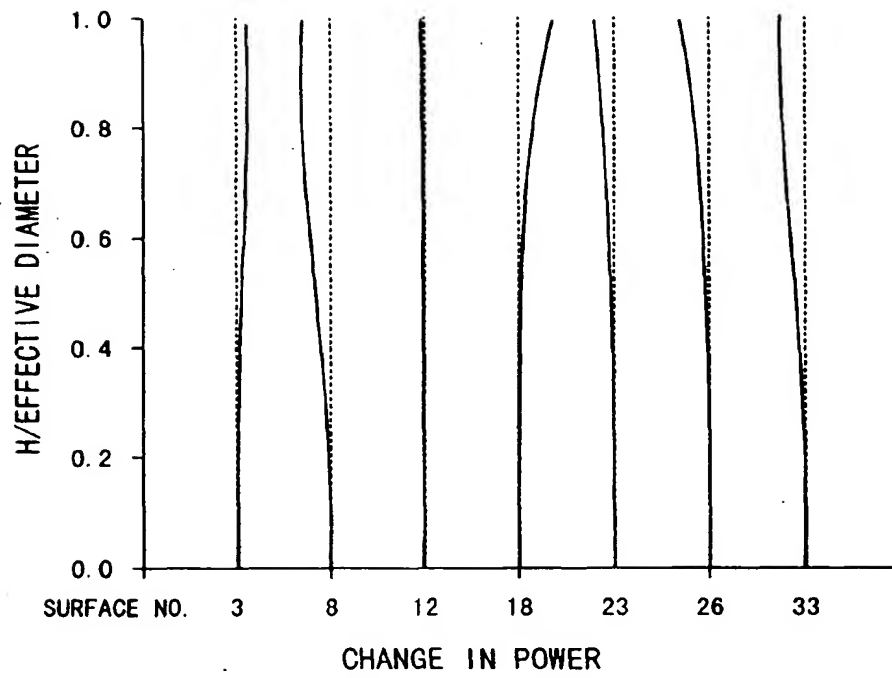


FIG. 68

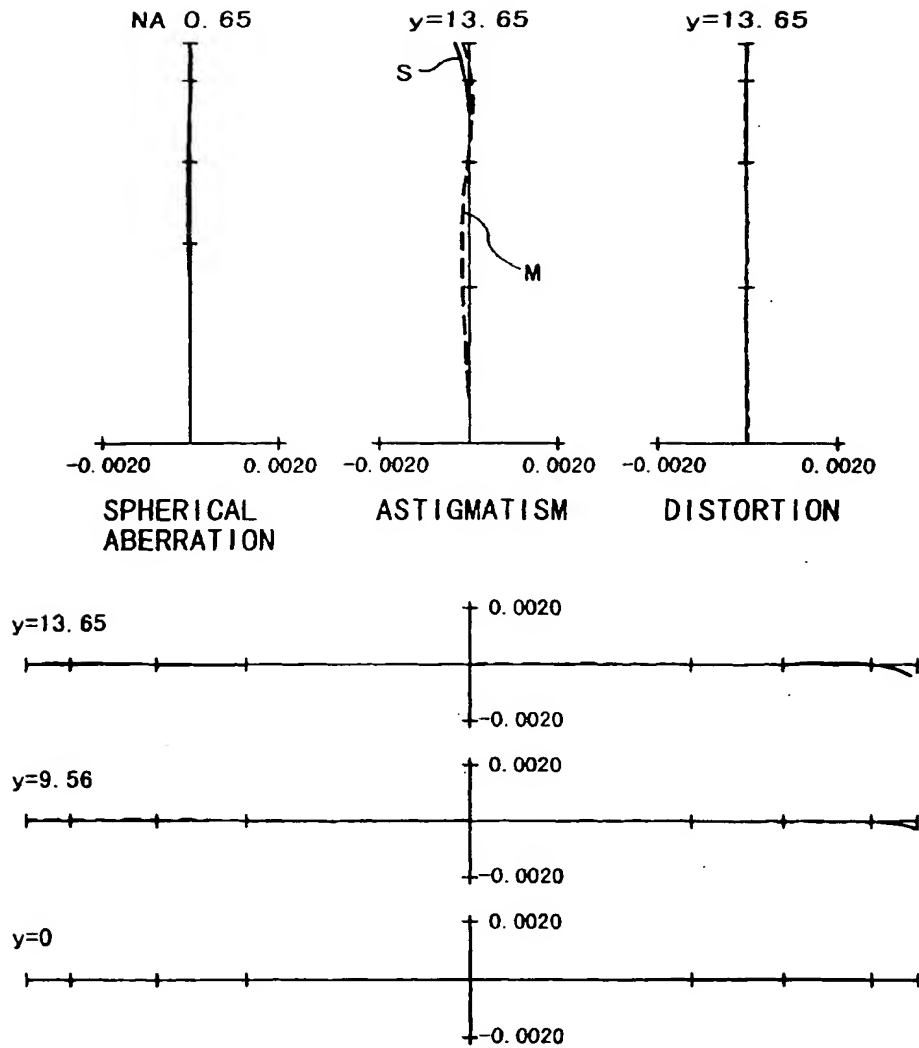


FIG. 69

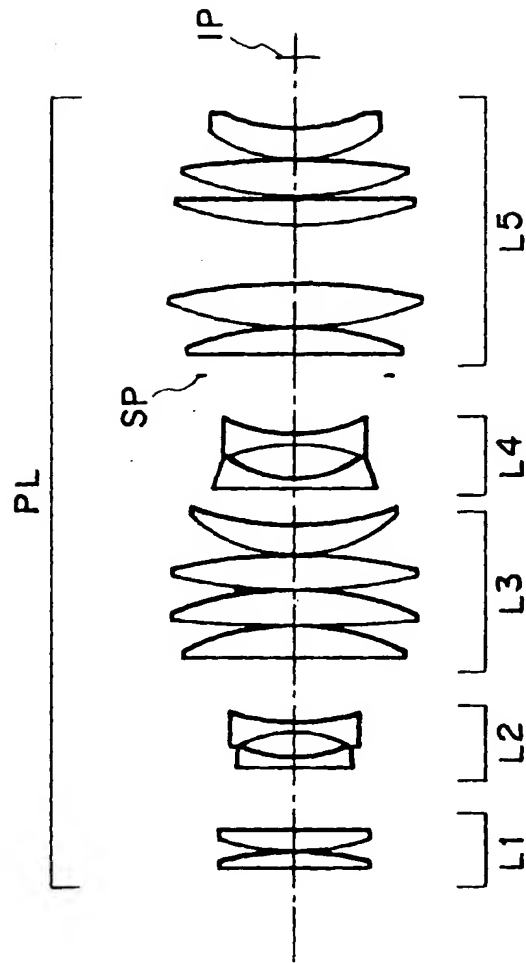


FIG. 70

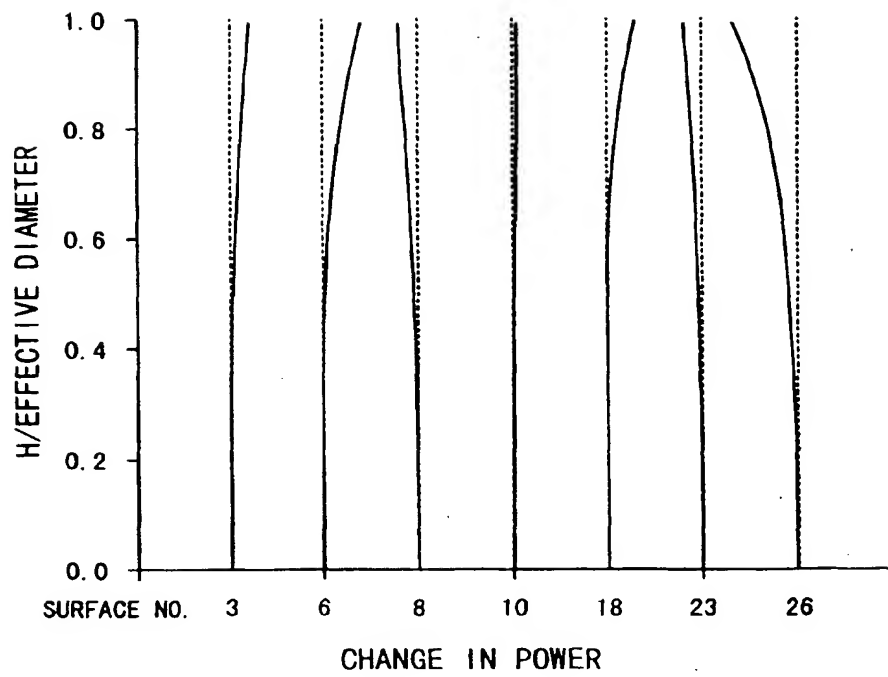


FIG. 71

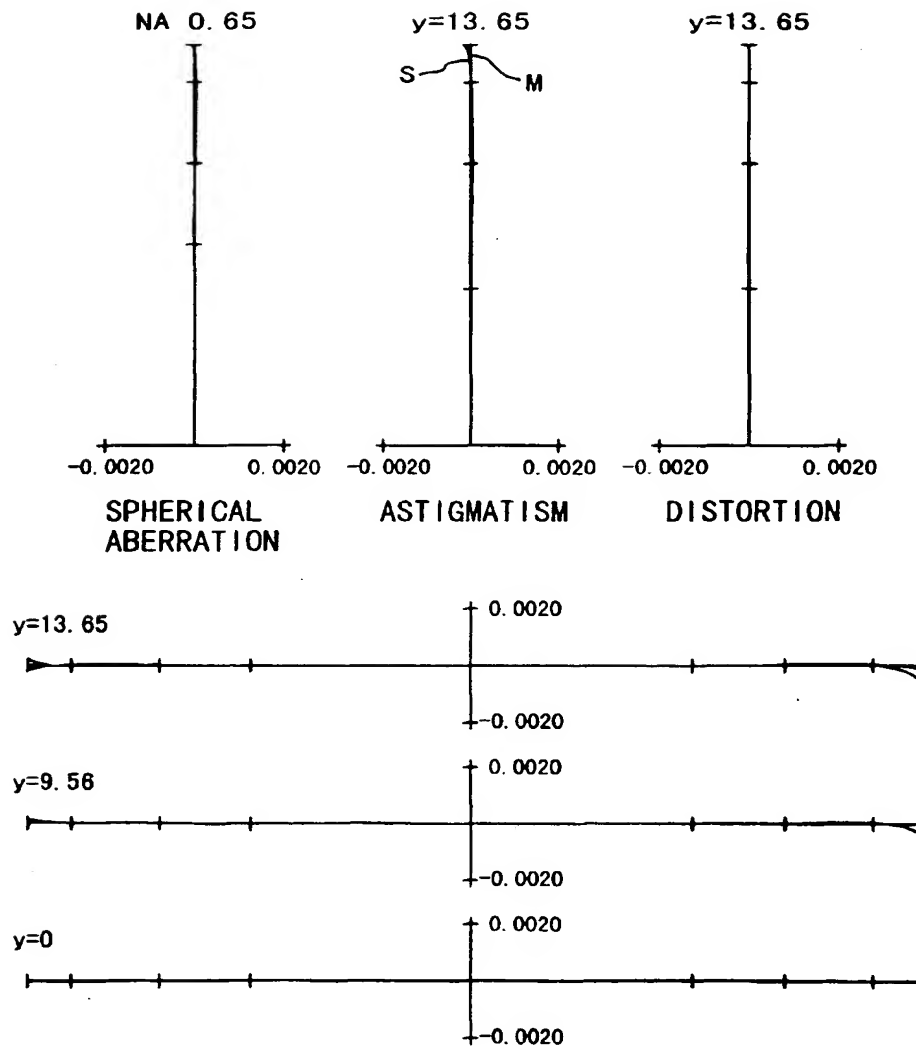


FIG. 72

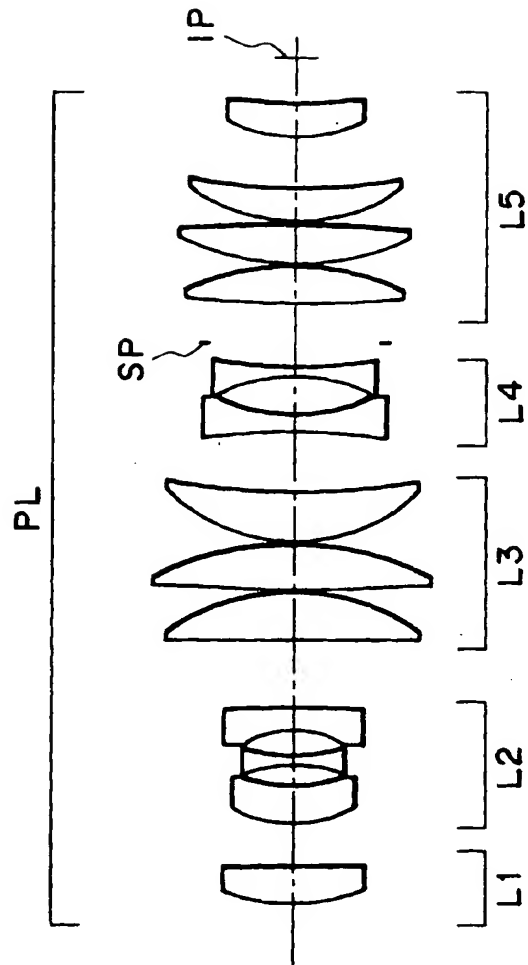


FIG. 73

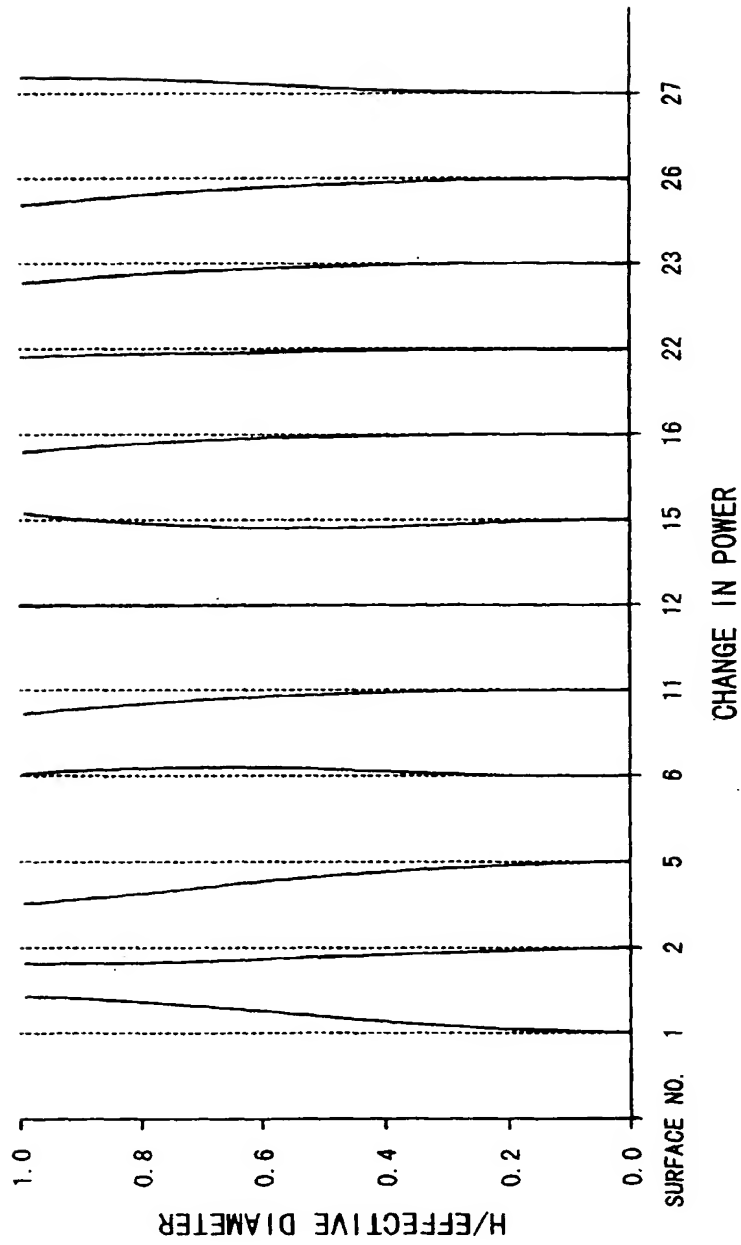


FIG. 74

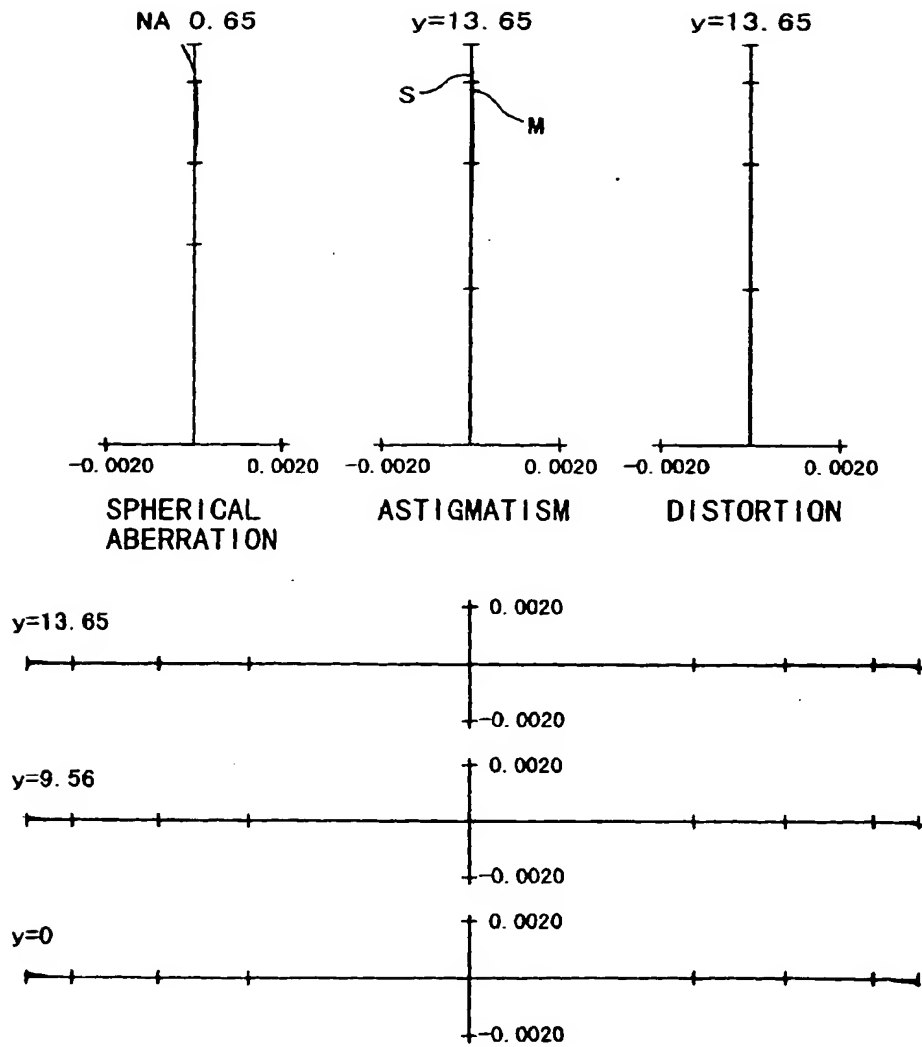


FIG. 75

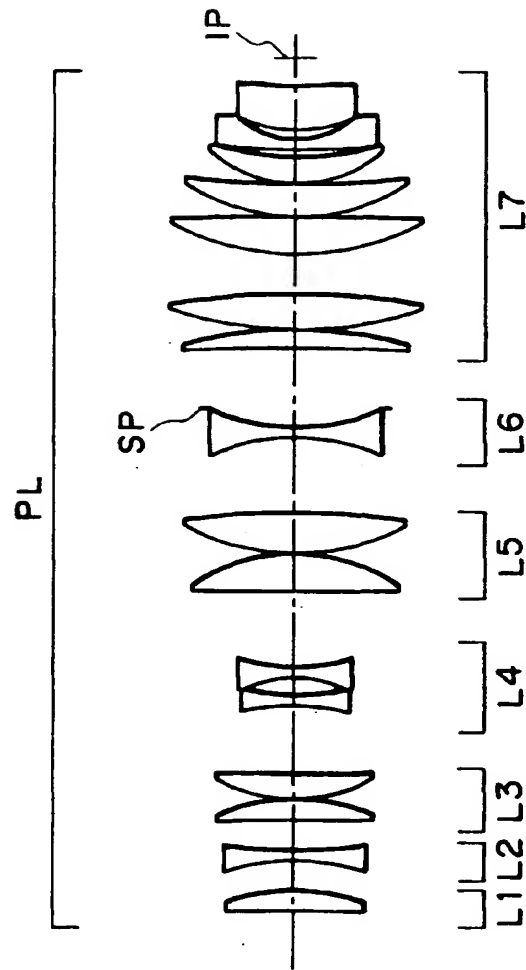


FIG. 76

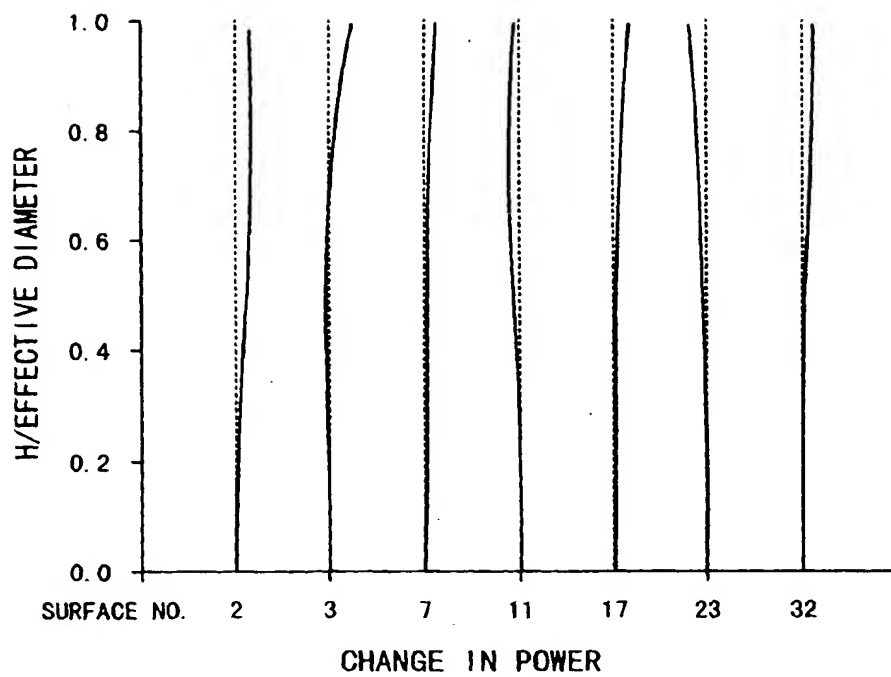


FIG. 77

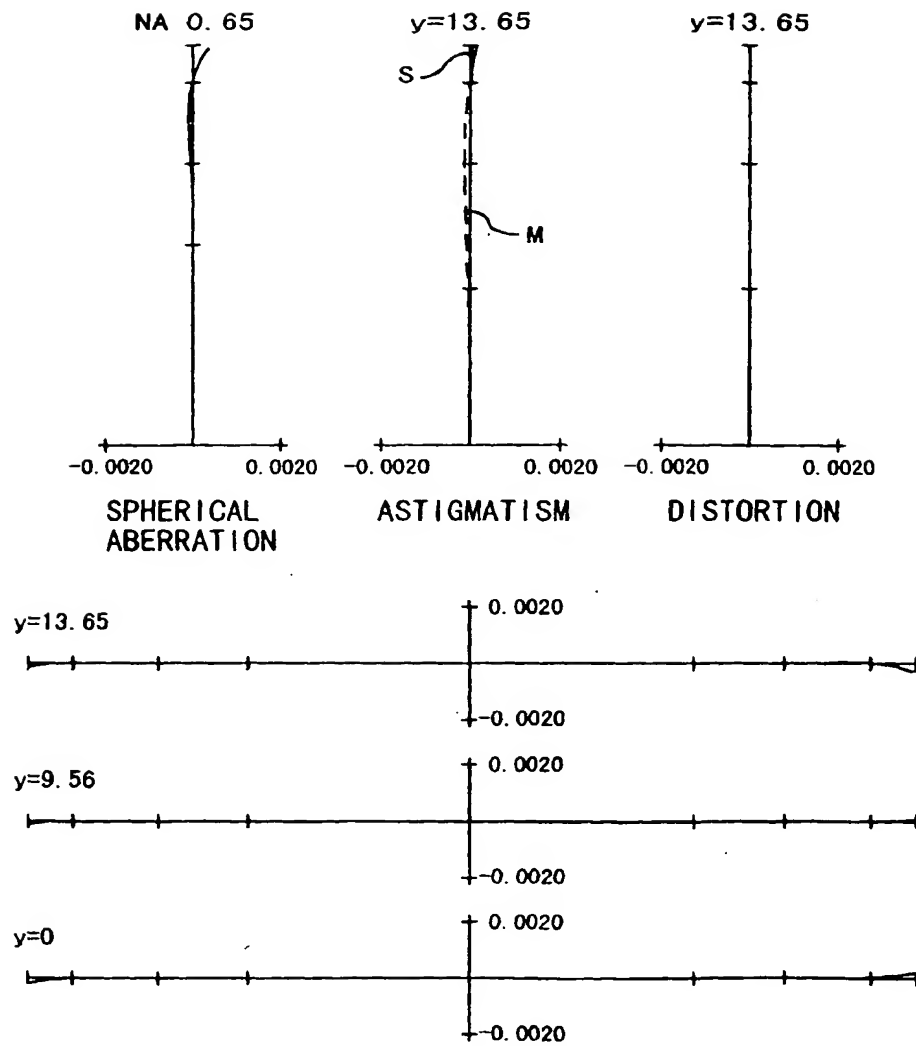


FIG. 78

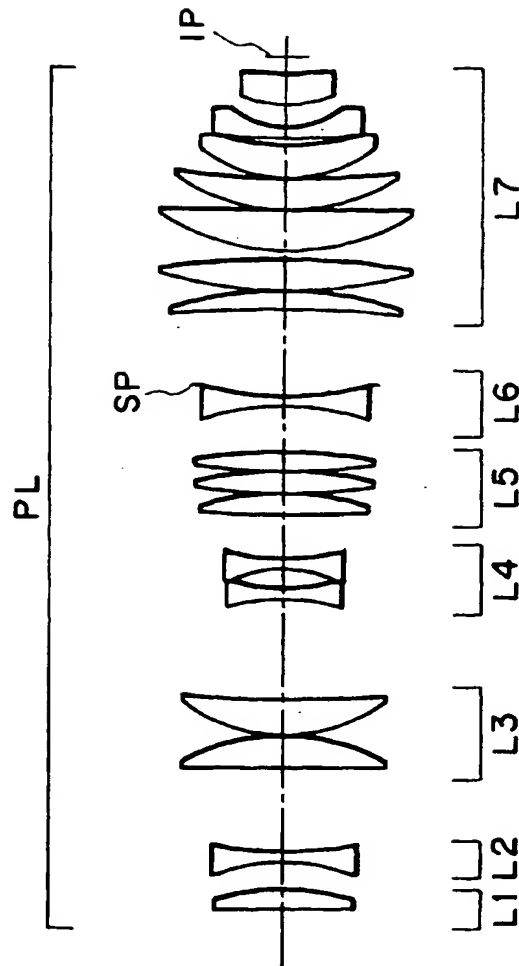


FIG. 79

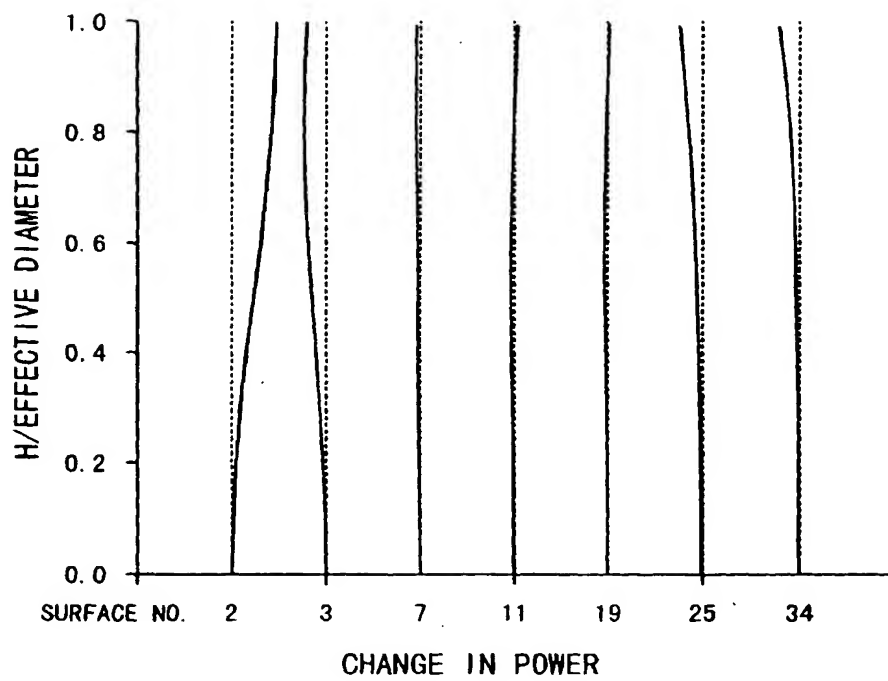


FIG. 80

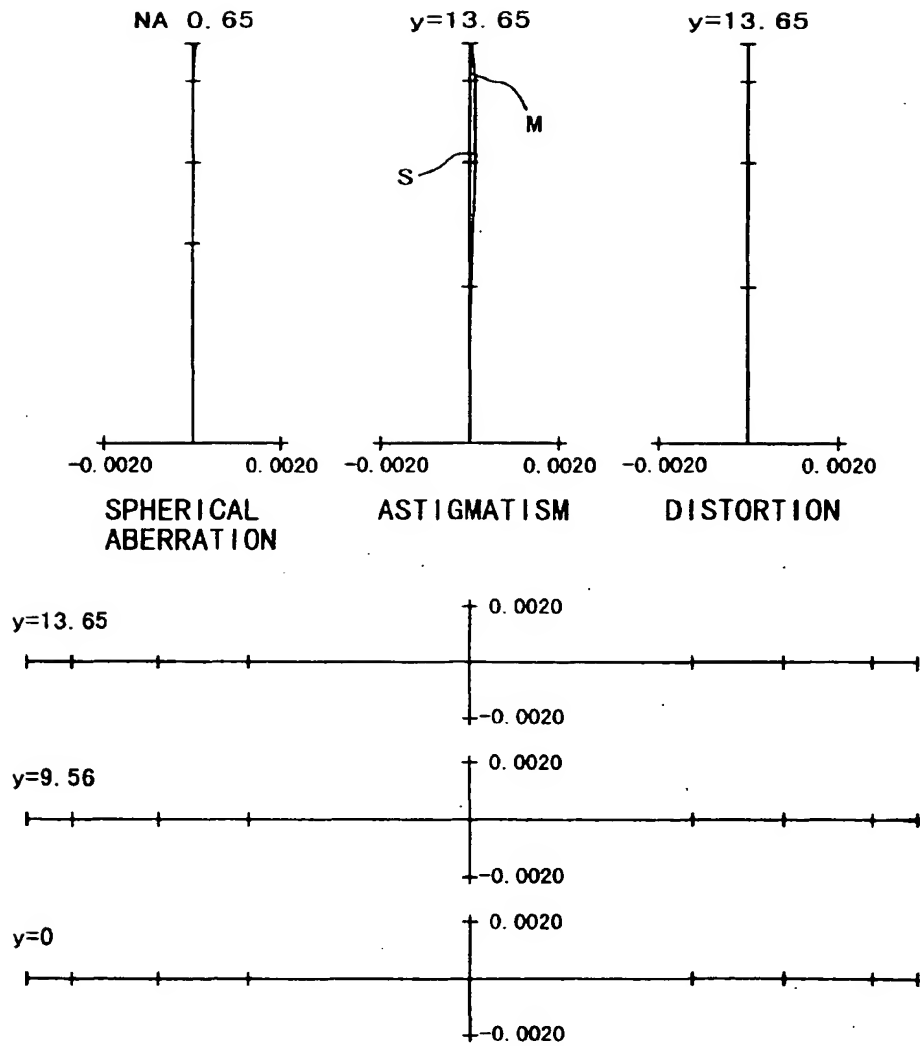


FIG. 81

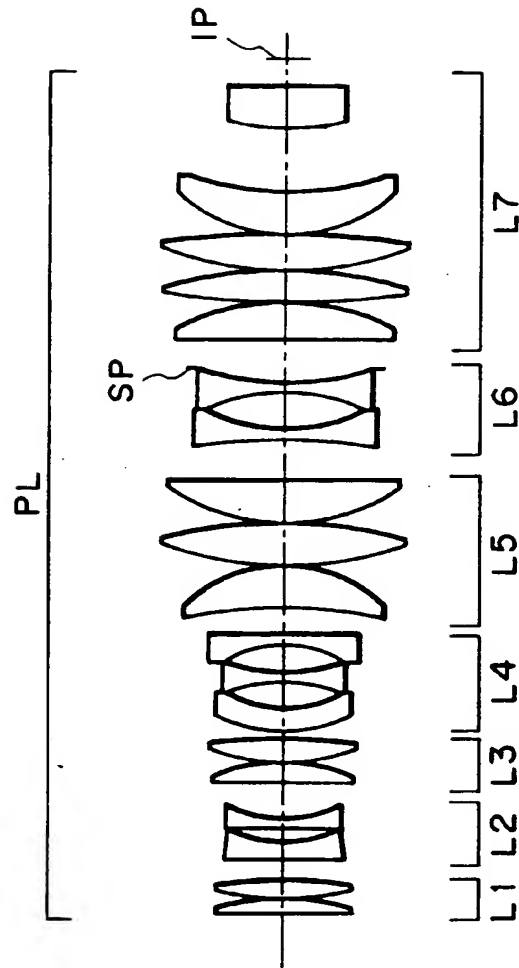


FIG. 82

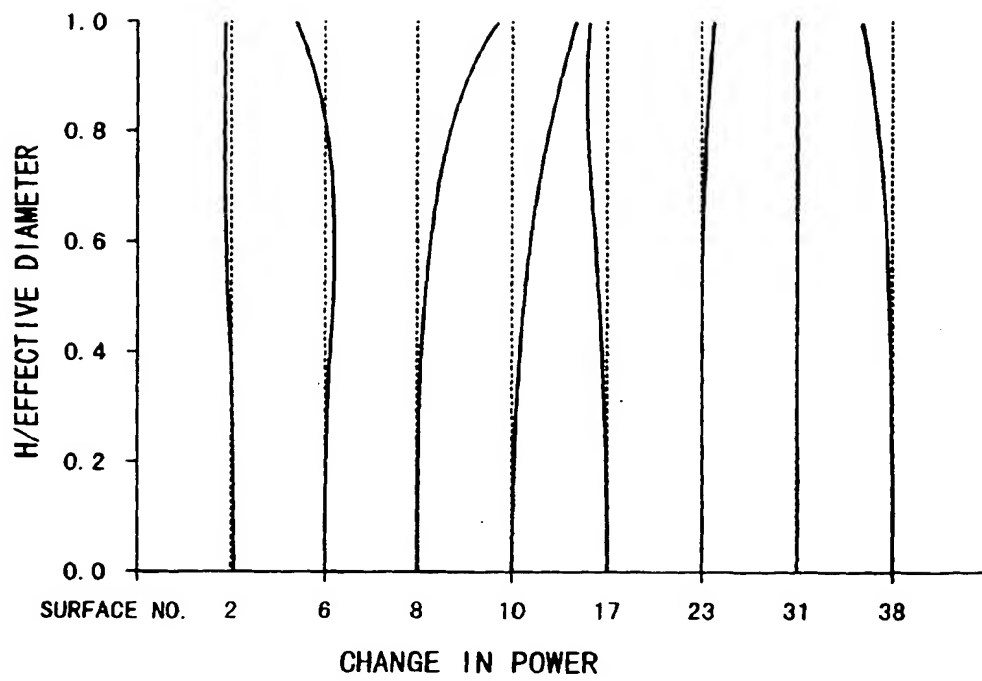


FIG. 83

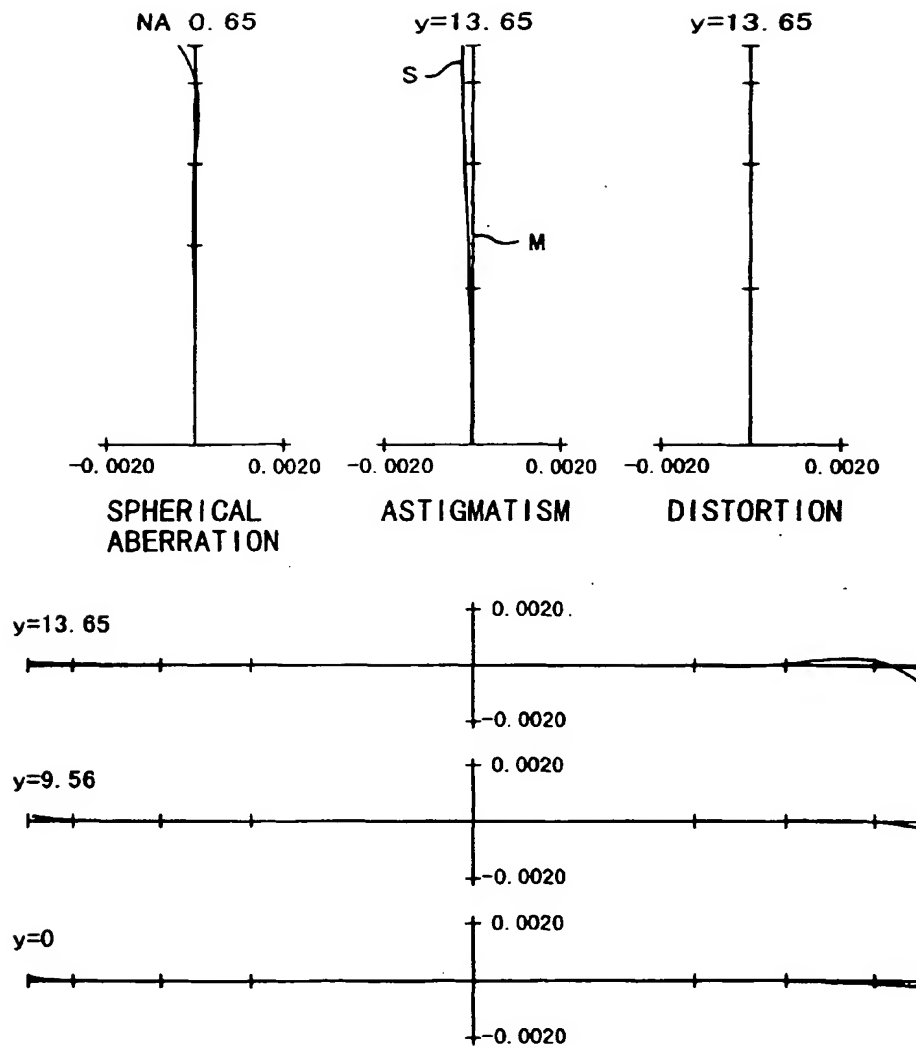


FIG. 84

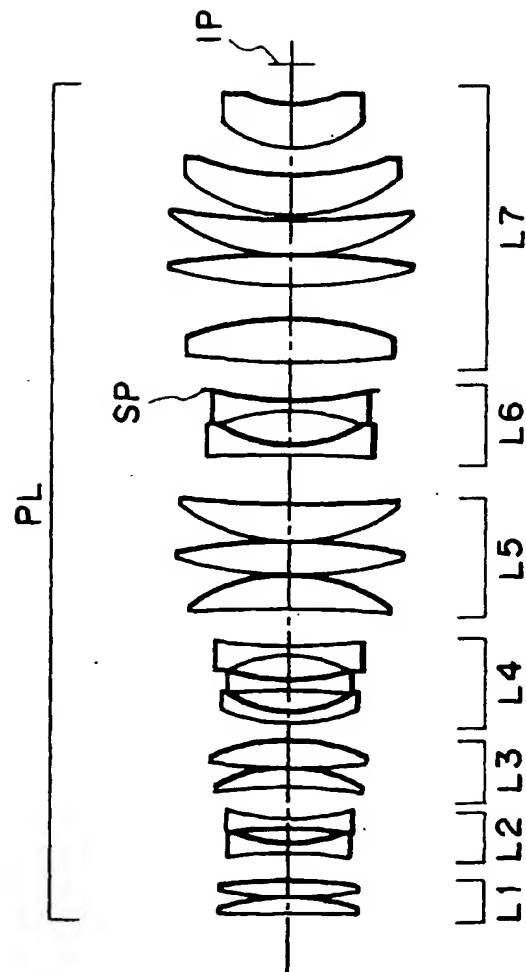


FIG. 85

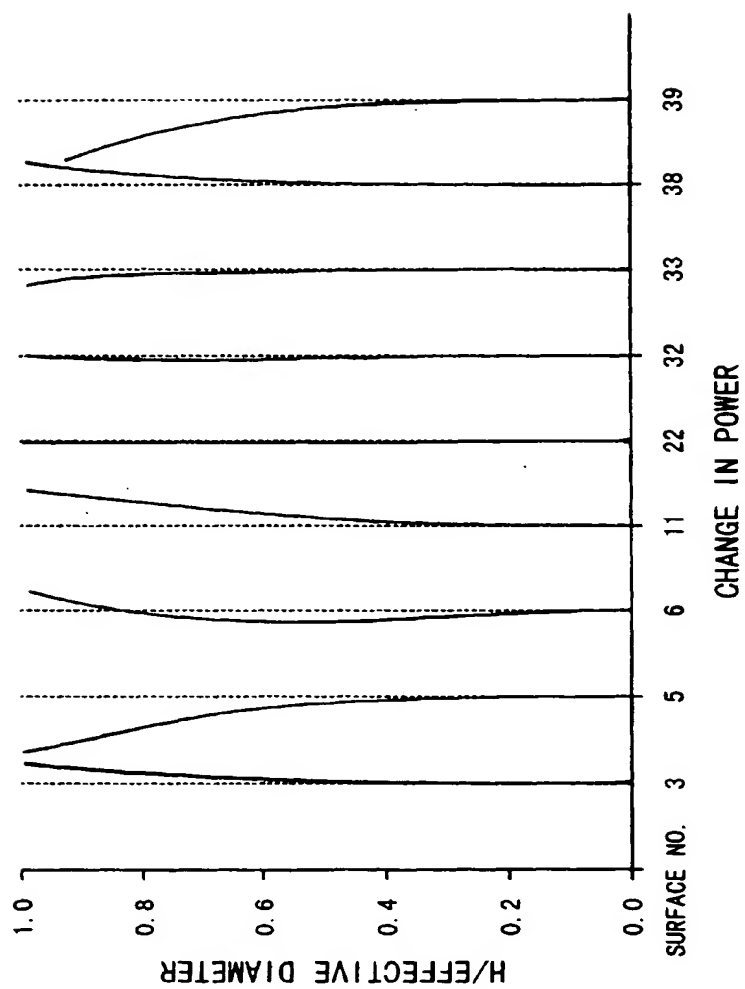


FIG. 86

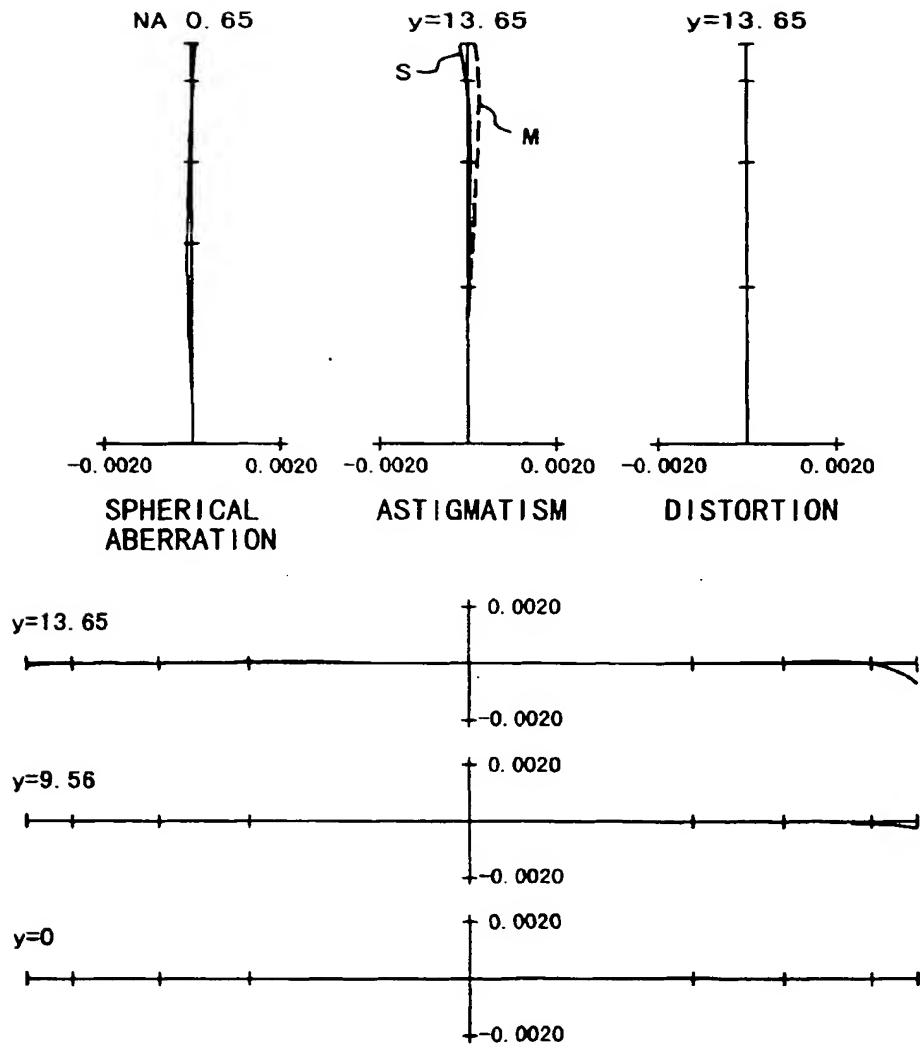


FIG. 87

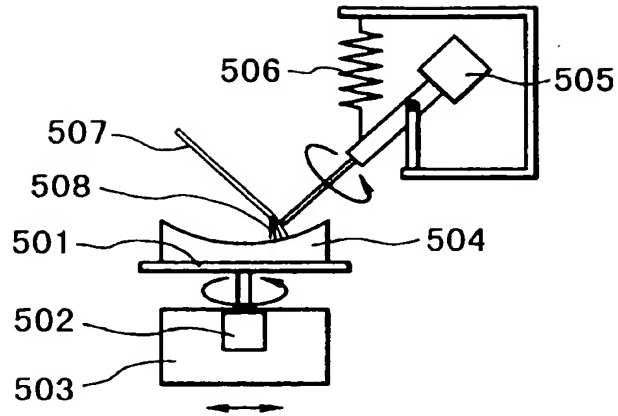


FIG. 88

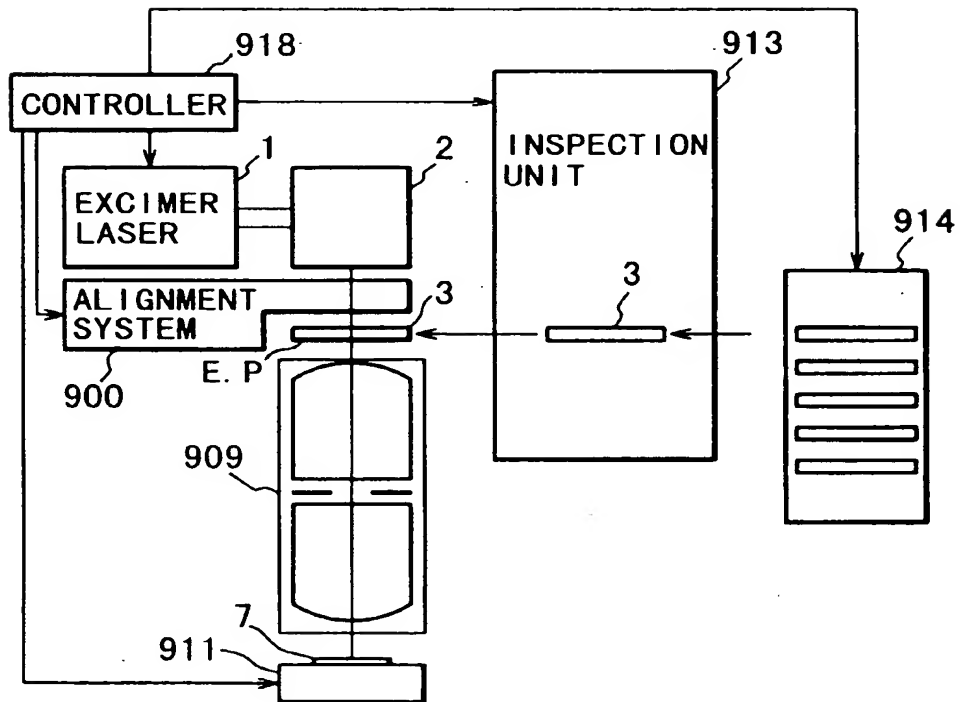


FIG. 89

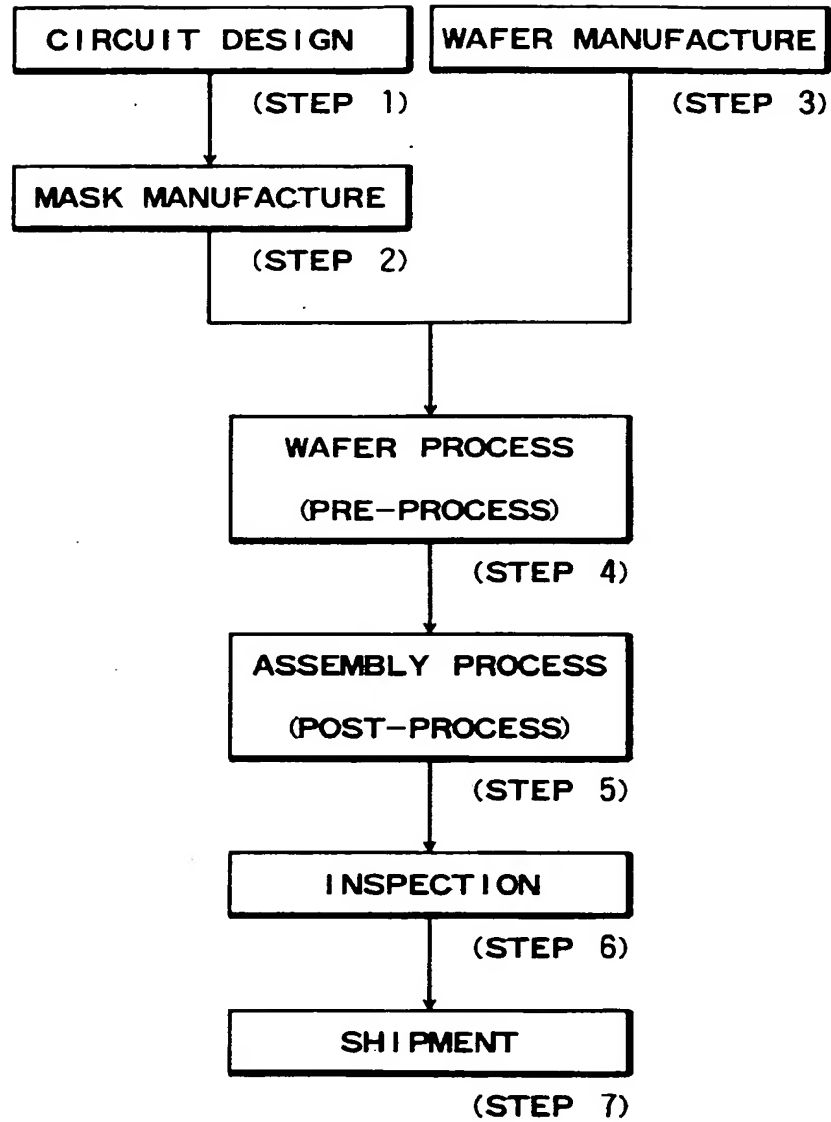


FIG. 90

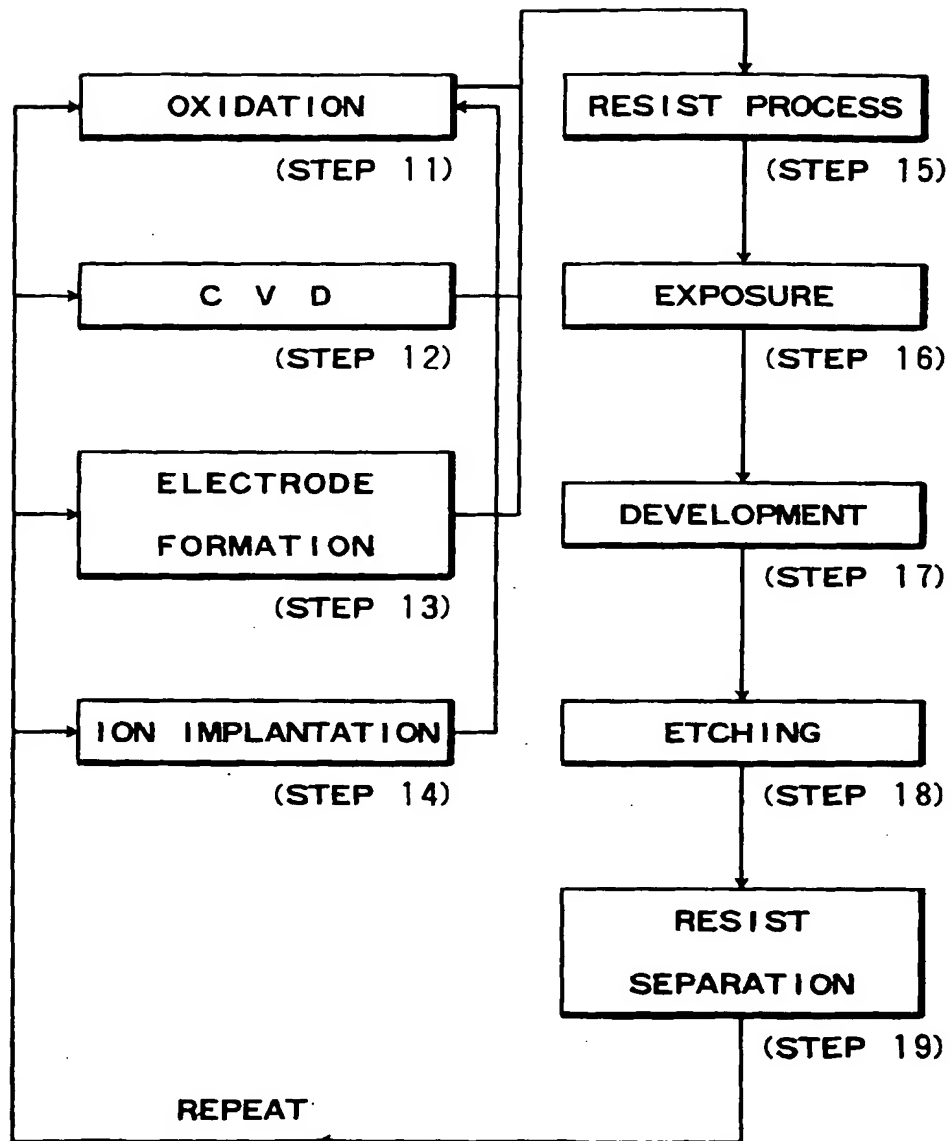


FIG. 9I